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STRESS-CORROSION CRACKING OF HIGH-STRENGTH ALLOYS

A Report To

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CONTRACT FULFILLMENT STATEMENT

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ABSTRACT

A stress-corrosion-cracking investigation was performed on one heat of 20%-nickel maraging steel and five heats of 18%-nickel maraging steel. These alloys were tested under three metallurgical conditions: (1) annealed and maraged, (2) cold-reduced and maraged, and (3) welded and maraged. Test environments included aerated distilled water, tap water, and 3% NaCl and 0.25% sodium dichromate solutions, as well as ambient air, 140°F water-saturated air, seacoast atmospheric exposure, hydrocarbon oil, soluble oil-water mixtures and trichoroethylene. Test methods included both two-point loaded beams and tensile-loaded samples having fatigue-crack stress-raisers.

Test results show that both the 20% and 18%-nickel grades of maraging steel are susceptible to stress-corrosion cracking in specific environments. With the 18%-nickel steel the susceptibility is found to increase with increasing titanium content. With both alloys, prior cold-reduction is found to lessen susceptibility.

Tests on 6Al-4V titanium show it to be immune to failure under these same test conditions, while limited testing on a new vacuum melted steel having 9% N, and 4% Co shows marginal susceptibility.

I. OBJECTIVES

The objectives of this program are:

A. Investigation of the stress-corrosion-cracking characteristics of at least three new high-strength alloys of interest for rocket-motor-case applications (6Al-4V titanium, 18%-nickel maraging steel, and 20%-nickel maraging steel), in addition to limited testing of vacuum-melted 9Ni-4Co steel.

B. Study of the environmental parameters that could affect the rate and extent of stress-corrosion cracking.

C. Determination of the effect of material parameters (composition, strength level, welding, and microstructure) on stress-corrosion susceptibility.

D. Continuation of the evaluation of protective coatings and other techniques for the prevention of stress-corrosion cracking.

II. DISCUSSION

A. IMPORTANCE OF STRESS-CORROSION TESTING

The nature of the premature failure of metals, when exposed to static stresses in specific environments, has long been the subject of intensive study. Such metal failure, generally referred to as stress-corrosion cracking, has received increased attention in recent years, with the development of the rocket industry. Here, the frequent use of high-strength steels, which are often highly susceptible to stress-corrosion cracking, coupled with the critical need for reliability of material performance, has underlined the importance of attaining a greater understanding of this mode of failure.

In the absence of a complete understanding of the mechanism involved, however, it is necessary to perform extensive testing under many environmental conditions and conditions of loading to evaluate the stress-corrosion-cracking behavior of all materials considered for rocket applications.

B. STRESS-CORROSION THEORY

Although many theories of stress-corrosion cracking have been proposed there are two principal mechanisms of interest. The continuous electrochemical process, and the alternate electrochemical-mechanical process. In the purely electrochemical process, crack propagation occurs by continuous anodic attack of the metal at the crack front; the second process proposes that a period of slow electrochemical attack alternates with fast mechanical fracture, leading to ultimate failure.

1. Electrochemical Mechanism

The electrochemical theory of stress corrosion was first proposed in 1940 by Dix[(1)*]. This theory states that the simultaneous action of the following three conditions will cause a metal to fail by stress corrosion:

a. A susceptibility to corrosion along continuous paths through the internal structure of the metal

b. A corrosive environment making paths of susceptibility anodic to the matrix of the metal

c. Applied or residual tensile stresses acting to pull the metal apart along these paths.

Cracking occurs in this case by selective corrosion, with the tensile stresses acting to open fresh anodic sites. The above theory is directly applicable to intergranular cracking such as occurs in some aluminum alloys. The theory was subsequently extended to include transgranular cracking[(2)]. In the case of transgranular cracking, the continuous paths are formed by slip planes and planes of precipitated constituents. Justification for this hypothesized mechanism is the measured increase in chemical activity along slip planes of plastically deformed crystals[(3)].

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* See References at end of text.

In other proposed electrochemical mechanisms it is stated that a prior existing path is not required. Uhlig[4] states that paths are continuously being formed due to plastic deformation at the tip of the advancing crack. He states that dislocation loops form zone to which interstitial elements such as nitrogen and carbon can differ forming cathodic sites. This mechanism may also account for the random branching paths observed in photomicrographs of stress corrosion cracks.

A third electrical mechanism that is not as well accepted as those cited above involves strain-induced transformation at the tip of the advancing crack - the transformed structure being anodic to the remainder of the metal. In mild steel, the transformed product is thought to be iron nitride[5]; in austenitic stainless steel, the transformed product is thought to be martensite.

A fourth electrochemical mechanism is based on film rupture[7][8]. The suggested sequence of events is as follows:

a. Electrochemical corrosion first causes grooves or notches to form on some portion of the stressed surface.

b. After some initiation period, the stresses at the tip of a notch become high enough to cause rupture of the naturally formed protective film.

c. Cracking proceeds because stress-induced film rupture causes anodic depolarization and dissolution of metal at the crack tip.

2. Mechanical Mechanisms

In each of the above mechanisms, the cracking proceeds by electrochemical dissolution of material. There have been other investigations which indicate that cracking was preceded, at least in part, by mechanical fracture.

Nielsen[9], in a study of oxides found in stress-corrosion cracks in stainless steel, states that formation of these oxides exerts sufficient lateral force to cause mechanical fracture at the root of the crack.

Edeleanu[10] and Keating[11] state that cracking proceeds by mechanical action with corrosion acting only to initiate the fracture. Microscopic studies by Edeleanu on migrating fractures indicate that crack propagation progresses by intermittent brittle fractures.

Although there is evidence both for and against the proposed mechanical and electrochemical modes of failure, there are two features of stress-corrosion cracks that are unique to any stress-corrosion process:

a. Cracks are formed under the combined action of stress and corrosion. They are not produced by the consecutive action of these agencies.

b. The corrosive media which cause stress-corrosion cracking are very specific for a given alloy and are not necessarily related to purely chemical corrosivity of the alloy in the particular medium. In these two respects, stress corrosion differs from fracture due to hydrogen embrittlement.

III. TEST METHODS

A. INTRODUCTION

In the original 2-year investigation of the stress-corrosion-cracking characteristics of high-strength alloys, a number of steels of then-current interest for rocket-motor-case applications were evaluated.[1] Since then the need for alloys of still higher strength in the rocket industry has focused attention on the maraging steels. The third-year program (see Table 1) was therefore directed to the study of the stress-corrosion-cracking susceptibility of a currently used titanium alloy (Table 2), two maraging steels (Table 3), and a new 9Ni-4Co alloy (Table 4).

The test environments, substantially the same as those in the original 2-year investigation, are (1) distilled water, (2) tap water, (3) salt water, (4) sodium-dichromate-inhibited water, (5) soluble-oil-inhibited water, (6) air, (7) high-humidity atmosphere, (8) trichloroethylene, and (9) cosmoline. These environments are considered to be representative of those to which rocket-motor cases would normally be exposed during fabrication, processing, or storage. One additional environment is included in the new program, that of seacoast exposure.

Both bent-beam and center-notch specimens were used in the investigation. The evaluation of results included microstructural studies, using both standard metallographic and electron-microscope techniques, in attempts to associate the failure mechanism with specific microstructural characteristics of the materials.

Protective coatings and surface treatments to prevent stress-corrosion cracking were also evaluated.

B. TEST SPECIMENS

1. Bent-Beam Test

The bent-beam test is the primary method used in this program. A total of 595 tests of this type have been conducted. Figure 1 shows an insulated bent-beam fixture with test samples mounted. Polycarbonate blocks 7.000 ±0.002 in. apart, attached to a stainless-steel holder, support the test specimen and insulate it from the holder. Specimens are machined to exact lengths to produce a maximum calculated outer-fiber stress that amounts to 75% of the mean 0.2%-offset yield strength. These length calculations are based on data supplied by the research and technology division of the United States Steel Corporation.(2) Figure 2 shows a representative plot of the stress-length relationship employed. These relationships were found by computer by U.S. Steel from formulas that resulted from a theoretically exact large-deflection analysis.

A four-point loading device is used to place the specimens into the holders. The use of four-point loading in this pre-stressing device eliminates possible local plastic deformation (which may have occurred during some earlier tests using a three-point loading fixture). Samples that were loaded into fixtures and then unloaded by means of the four-point device showed no measurable residual distortion, which indicated that the yield strength of the material had not been exceeded during stressing.

2. Center-Notch Test

The configuration used in the center-notch test is shown in Figure 3. It consists of a 1-3/4 by 8-in. tensile specimen containing a central notch, which is produced in a two-step process: first, a 0.06- by 0.57-in. slot is Elox-machined and extended at each end by very-narrow, Elox-machined notches of 0.001-in. root radii; then these notches are extended by means of fatigue cycling to obtain fatigue cracks of controlled dimensions.

When a specimen of this type is stressed, the elastic field parameter (K, in ksi $\sqrt{\text{in.}}$) at the tip of the crack is represented by

$$K = \sigma \left(W \tan \frac{a\pi}{W}\right)^{1/2}$$

where W is the specimen width (in.), a is one-half of the total crack length (in.), and σ is the nominal stress (ksi). Simultaneously, the crack-extension force (G_c, in in.-lb/in.^{2}) may be obtained from

$$G_c = \frac{K_c^2}{E}$$

where E is the elastic modulus of the material, and K_c is the critical value of K at which crack propagation occurs in rapid tensile testing.

These center-notch specimens are stress-corrosion tested in Baldwin creep-test machines (Figure 4). Dead-weight loading is applied to a 20-to-1 lever arm to give a K value at the crack tip amounting to 75% of the K_c value. The test solution is applied in a polyethylene cup cemented to the specimen in the notched area before loading. An automatic timing device is used to record the time to failure.

C. TEST ENVIRONMENTS

The environments described below were used to study stress-corrosion-cracking susceptibility.

1. Laboratory Air

This environment was used as a standard for comparison with other environments. The temperatures ranged from 70 to 78°F, and the relative humidity ranged primarily from 35 to 50%. No stress corrosion failures have yet occurred in this environment, even with the most susceptible alloys.

2. Distilled Water

This environment was also used as a standard for comparison with other environments. The pH of the distilled water was found to be 7.0. Continuous aeration was maintained with filtered air during the test.

3. Aerated Tap Water

Tap water represents the medium frequently used to clean solid-propellant rocket-motor cases. It is also used in the hydrostatic testing of pressure vessels, particularly chambers constructed of corrosion-resistant alloys. Azusa well water with a pH of 7.6 was used in the Aerojet tests; the water analysis is summarized in Table 5.

4. Aerated Salt Water

An aerated 3% solution of sodium chloride in distilled water was used to simulate a severe marine environment. The pH of this solution was 7.0.

5. High Humidity

Samples are placed in water-saturated air at 130 to 140°F to simulate a severe atmospheric condition.

6. Seacoast Exposure

Samples were placed on an outdoor test rack (Figure 5) at the Aerojet Newport Beach test facility for testing in a natural seacoast environment. This rack, placed on a rooftop approximately 200 yards from the beach, faced the beach without obstruction.

7. Aerated Chromate Solution

This environment, created by 0.25% by weight of sodium dichromate dissolved in distilled water, represents the medium frequently used in flushing solid-propellant rocket-motor cases and in the hydrostatic testing of pressure vessels, particularly those constructed of low-alloy steels. The pH of this solution was between 4.5 and 5.0.

8. Soluble-Oil Solution

This environment, a distilled water solution of 4% by volume of Chevron soluble oil, represents one of the fluids used in the hydrostatic testing of pressure vessels. Aeration was discontinued in this test medium because of foaming. The pH was between 9.5 and 10.0.

9. Cosmoline

Rust-inhibiting oil conforming to MIL-C-14201A, Grade 2, was used to represent the rust-inhibiting compound sometimes used on rocket-motor-case material during manufacture, transit, and limited storage prior to propellant installation.

10. Trichloroethylene

This is a chlorinated, degreasing solvent commonly used on rocket-motor cases.

11. Bayonne Atmosphere

Samples were exposed in a test rack maintained by the International Nickel Company in the heavy industrial atmosphere of Bayonne, New Jersey.

12. Kure Beach

Samples were exposed at the 50-foot lot by the International Nickel Company at Kure Beach, North Carolina. This is a much more severe location than the Newport Beach site.

13. Natural Seawater Immersion

Samples were immersed in natural flowing seawater by the International Nickel Company at Harbor Island, North Carolina.

D. ALLOY PROPERTIES

1. 6Al-4V Titanium

This high-strength titanium alloy is being widely used for pressure vessels and rocket-motor cases. It has excellent fabricability and can be heat-treated to high strength levels. The chemical and mechanical properties of the heat of the alloy that was tested are shown in Table 2. The sample was tested in three metallurgical conditions: annealed, quenched and aged, and as-welded.

The annealed condition employed in the testing was the condition in which the alloy was received. No further thermal treatment was employed, but 0.010 in. was ground from each side of the samples.

The quenched-and-aged condition was attained by means of a 1675°F solution-anneal followed by a water-quench and an 8-hour aging treatment at 900°F. Some distortion of the samples was found to occur during quenching, but this was largely overcome by aging while the specimens were clamped tightly in a stainless-steel fixture. After aging, 0.010-in. was ground from each side of the specimen.

Some of the annealed material was welded, using the tungsten-iner-gas (TIG) process with commercially pure titanium filler wire. The samples were exposed in the as-welded condition with a 30% weld reinforcement.

2. 20%-Nickel Maraging Steel

This is a high-strength steel that will attain desired strengths in a single aging treatment. Low G_c values were obtained with this alloy, indicating a high degree of notch sensitivity. Its chemical and mechanical properties are shown in Table 3. The single heat of 20%-nickel maraging steel was tested in four conditions: annealed and aged; 50% cold-worked and aged; 75% cold-worked and aged; and welded and aged. Figure 6 shows the effect of prior cold-work on the mechanical properties of the aged material. Welding was performed on the 20%-nickel steel with an automatic TIG welder without filler metal. Mechanical tests indicated an 85% joint efficiency. All aging was performed at 850° for 4 hours. With the welded and the annealed samples, aging was preceded by a 1-hour stabilizing treatment at -100°F.

3. 18%-Nickel Maraging Steel

This alloy has a nominal composition of 18% nickel, 9% cobalt, and 5% molybdenum; it is receiving increased attention for application in the aerospace industry. Because of the high interest in this alloy, five heats of this material were tested. Two heats were purchased for this program, while the other three were remnants from an earlier Aerojet program. The chemical and mechanical properties are given in Table 3.

Figure 7 shows the effect of titanium content on the mechanical properties of annealed material aged at 900°F for 3 hours. These data show that increases in titanium content will increase the ultimate and yield strengths of maraging steel with only slight lowering of the reduction-of-area and notch-sensitivity values. Figure 8 shows how the yield and ultimate strengths may be raised even more by cold reduction prior to aging, again at the expense of a lower G_c value; however, even the lowest G_c value obtained with the 18%-nickel steel (156 in.-lb/in.^{2} at a yield strength of 354 ksi) is almost 3 times higher than the highest obtained with the 20%-nickel alloy (58 in.-lb/in.^{2} at 291 ksi).

The 18%-nickel steel was welded by means of the TIG process without filler metal. Mechanical tests indicated a 94% joint efficiency.

In addition to the 18%-nickel samples listed in Table 2, tests were conducted on samples machined by the Research Laboratory of International Nickel Company. Properties of these samples are shown in Table 6.

4. <u>9-Nickel, 4-Cobalt Steel</u>

This is a vacuum cast martensitic alloy presently in the development stage. It is reported to have exceptional notch toughness along with high yield and ultimate strengths. This alloy is reported to be available at two strength levels - HP-9-4-25 containing 0.25% carbon and HP-9-4-45 containing 0.45% carbon. Because of late delivery only limited testing of one alloy - (HP-9-4-25) was possible.

The chemical analysis and mechanical properties of this alloy are shown in Table 4. The ultimate and yield strengths were found to be less than indicated by preliminary technical data furnished by Republic Steel Company. This discrepancy may be attributed to 0.002- to 0.006-in. of partial decarborization on the samples.

5. <u>H-11 Steel</u>

This alloy (Vascojet 1000) when tempered at 900-950°F was found in the initial 2-year program to be highly susceptible to stress-corrosion-cracking. Consequently, it was used as a basis for the evaluation of protective coatings. The following heat treatment was employed: 1900°F for 40 min, followed by an air quench, and then aging at 950°F for 3 hours.

E. SPECIMEN PREPARATION

1. Maraging Steel Specimens

The edges of the steel samples were milled to size before heat treatment. Very slight scaling occurred during the 900°F heat treatment in air. As shown in Table 7, the first groups of specimens tested were hand-cleaned; the scale was removed by using 360-grit emery paper. Later the procedure was changed to vapor-blast cleaning with 400-mesh alumina powder. Chemical cleaning to remove heat-treat scale was avoided to eliminate any possibility of chemical embrittlement. The maraging steel samples prepared by the International Nickel Company, and tested by Aerojet, were reported by INCO to have been ground after maraging.

All test samples prepared at Aerojet were transverse to the major rolling direction, while specimens supplied by the International Nickel Company were grain-oriented in the longitudinal direction.

2. Titanium 6Al-4V Specimens

These specimens were surface-ground 0.010 in. on a side to remove a surface layer contamination which is known to occur with this alloy during heat treatment. Without the grinding operation the full mechanical properties of this alloy cannot be attained.

IV. TEST RESULTS

A. BENT-BEAM TESTS

Dimensions and surface conditions of the bent-beam samples are shown in Table 7. Samples were stressed to a calculated value representing 75% of the 0.2%-offset yield strength.

1. 6Al-4V Titanium

Bent-beam stress-corrosion test results are shown by environment in Tables 8 through 18. No failures have been observed with the 6Al-4V titanium alloy in any of the three metallurgical conditions tested. Typical microstructures of this alloy are shown in Figure 9.

2. 20%-Nickel Maraging Steel

In the annealed-and-aged condition the 20%-nickel maraging steel was found to crack rapidly in distilled-water, salt-water, high-humidity, trichloroethylene, and seacoast atmosphere. The stress-corrosion cracking process was found to follow a branching pattern, as shown in Figure 10. Photomicrographs (Figure 11) indicate that the cracking is intergranular in nature.

When the alloy had been cold-worked prior to aging, a marked increase was noted in the time-to-failure. Random failures occurred after long exposure to distilled water, tap water, high-humidity, and seacoast atmosphere. The salt water immersion (Table 10), which caused the most rapid failures with the annealed-and-aged material, caused no failures with the cold-worked-and-aged material. However, the tap-water environment (Table 9), which caused no failures with the annealed-and-aged material, caused some long-term failures in the cold-worked-and-aged material.

The welded material was found to have an even shorter time-to-failure than the annealed-and-aged material of the same heat. All failures were found to occur in the weld heat-affected-zone. Welded samples failed in tap water, salt water, distilled water, trichloroethylene, and in high-humidity environments.

3. 18%-Nickel Maraging Steel

In the annealed-and-aged condition, two or more heats of 18%-nickel maraging steel showed some failures in distilled water, tap water, salt water, high-humidity, and soluble oil as well as in industrial and seacoast atmospheres. In addition, one heat (Group I-1, Table 3) was found to fail in the 0.25%-sodium-dichromate, and trichloroethylene environments. In general, it was found that the failure times were reduced as the titanium content of the alloy was increased, although some exceptions were noted. Figures 12 and 13 present photomicrographs of failures of annealed-and-aged, 18%-nickel maraging steel. As with the 20%-nickel steel, the cracking had a branching intergranular pattern.

The tests in the trichloroethylene environment were the exception to this mode of fracture as shown in Figure 14. These cracks are straight, wide and rounded at the root. It appears that chemical dissolution along the stress corrosion crack has occurred in the trichloroethylene environment.

When the 18%-nickel alloy was cold-reduced 50% before aging, the time-to-failure was found to increase (decreasing susceptibility to failure). The effect of the prior cold reduction on failure time, however, does not appear to be as pronounced with the 18%-nickel grade material as with the 20%-nickel grade. Along with the change in time-to-failure, a marked change in mode of failure was noted. Figures 15 and 16 show failures of 50% cold worked and aged material showing the cracks propagating at acute angles to the specimen surface, quite unlike the cracking of annealed-and-aged samples.

Welded samples of heat 3960504 (Group I-W) was found to have a shorter mean time-to-failure than the annealed and maraged material (Group I4) in the tap water, salt water, soluble oil and high-humidity environments, but a longer mean lifetime in the distilled water environment. Welded samples were found to fail with cracks originating in the weld heat-affected-zone. Figure 17 shows views of a welded specimen which failed.

The specimens of the three heats of material prepared by the International Nickel Company showed much greater resistance to stress-corrosion cracking (although failures were experienced) than the material used by Aerojet as shown by the results in Table 18. Some of the material parameters of the INCO-prepared specimens which differ from the Aerojet-prepared specimens and which might affect the material's susceptibility to stress corrosion cracking are shown below: The INCO material was surface ground after maraging (cold working of surface), showed a smaller grain size, showed some compositional difference, and was tested in the longitudinal grain direction (which is generally more resistant to failure).

4. 9Ni-4Co Alloy

Because of late delivery this alloy was tested in only four environments: distilled water, tap water, salt water, and 140°F with high humidity. The alloy was found to fail in stress corrosion after the 400°F and 600°F aging treatments in the high humidity atmosphere and after the 400°F treatment in the distilled water environment. No failures occurred in the other two environments or, with material that had been tempered at 800°F in any of the environments.

The cracks were found to be of the fine, non-branching, intergranular type noted in other martensitic steels.

B. CENTER-NOTCH TESTS

Roughly 100 center-notch specimen tests were conducted during this program. The tests were confined to four environments: distilled water (results, Table 19), salt water (Table 20), sodium dichromate solution, (Table 21) and soluble oil solution (Table 22).

1. 6Al-4V Titanium

No failures occurred in center-notch testing of this alloy in any of the four environments.

2. 20%-Nickel Maraging Steel

Annealed-and-aged material (Group H-1) failed rapidly in the distilled water and in the salt water environments. Samples from this group did not fail in the chromate or soluble oil solutions, thus supporting the results of the bent-beam tests.

The cold-worked and aged material (Group H-2 and H-3) was found to have a much longer time-to-failure than the annealed-and-aged material in the distilled water and salt water environments. This is again in agreement with the results of the bent-beam tests.

3. 18%-Nickel Maraging Steel

Both the annealed-and-aged and 50% cold-worked-and-aged materials were found to fail, in order of severity, in salt water, distilled water and sodium dichromate solution. The time-to-failure in the salt water environment (Table 20) was found to decrease with increasing Kc values for the test materials.

With material of a given titanium level, the time-to-failure is shorter for the cold-worked material than for the annealed material. However, in the bent-beam testing, the material which had been cold-worked earlier, was found to have a substantially longer lifetime then the annealed material. It appears that, in the 18%-nickel-grade maraging steel, this longer lifetime is the result of residual surface compressive stresses rather than a higher inherent resistance to stress-corrosion fracture.

4. Effect of Varying Stress Level

A series of stress corrosion tests were conducted with one heat each of 20%- and 18%-nickel maraging steel at varying loads. The results are shown graphically in Figure 18 with the applied loads shown as corresponding K values, according to the formula. These data show that for both of the maraging steel alloys tested, the time-to-failure is a linear function of the applied load until a critical value is reached. Squaring this critical K value and dividing by the elastic modulus of the material, a value of G_c is obtained that represents the minimum energy for stress corrosion crack growth. These G_c values are roughly equal to 200 in.-lb/in.^{2} for the 18%-nickel material and 20 in.-lb/in.^{2} for the 20%-nickel material.

For comparison, similar tests were made on a heat of vacuum-melted AMS 4335 material. The failure time was found to be independent of load for this material.

C. COATINGS EVALUATION

Table 23 presents the final results of the coating ev[illegible]ation program. Fifteen coatings (based largely on vendor-developed technolog[illegible] [illegible]re tested in three environments. The coatings were applied to H-11 steel. No single coating was found that would prevent stress corrosion cracking in all three media: salt water, high humidity and seacoast atmosphere. Results as reviewed below can be compared with uncoated H-11 steel base metal which showed average failure times in these three environments of 16, 64, and 116 hours respectively.

1. Aerated Salt Water

The chromate-inhibited epoxy systems were by far the most effective in preventing stress-corrosion cracking in this environment. Two of these coatings, 454-1-1 and 463-1-5, either applied as successive coats or when applied separately showed no failures in these tests in over 3000 hours of exposure. A similar coating, 463-4-8, protected the metal for roughly 500 hours, after which adhesion loss caused rapid-stress corrosion failure.

A substantial increase in lifetime of base metal was also obtained with a vinyl coating, AM-33, which failed after approximately 3000 hours.

2. High Humidity Environment

Two coatings based on zinc, zinc silicate Type 4 and inorganic zinc 11 with an epoxy top coat, were found to prevent cracking in this environment (for over 3000 hours), but both of these coatings showed very little protective ability in the salt water immersion tests. However, the inhibited epoxy 454-1-1, the polyurethane, X-500 and the vinyl coating, AM-33, all had relatively long mean failure times in high humidity as well as in salt water.

3. Seacoast Exposure

Four coating systems were found to prevent stress-corrosion cracking in this environment for the period of these tests (2900 hours). One of these was the vinyl coating AM-33, the others were all of the zinc-based types (see Table 23).

D. ELECTRON MICROSCOPE FRACTOGRAPHS

Four failed specimens were selected for study by the electron microscope. Identification of the samples and approximate location of the areas for fractographic study are shown in Figure 19. Parlodion replicas with chrome-carbon shading were used in making the fracture replicas. Because of the roughness of most of the surfaces, some difficulty was encountered in the stripping of the replicas. These fractographs are briefly described below.

1. H-11 Steel

The H-11 steel sample, shown at the top of Figure 19, has a single fracture at right angles to the surfaces of the specimen. This sample failed after 2.5 hours of exposure to aerated salt water.

Figure 20 shows a typical brittle fracture in a view taken from the center of the sample (view "A", Figure 19).

The view in Figure 21, taken from the corner of the sample at which the stress-corrosion fracture originated, shows some micro-structure modeling that may have been caused by corrosion.

2. 20%-Nickel Maraging Steel

The 20%-nickel maraging steel specimen shown in the center of Figure 19 has a typical, branching, crack pattern. This sample is of the annealed-and-aged group (H-1) and failed after 1 hour in 0.25%-sodium-dichromate solution. It was selected for examination because of its complete freedom from rust.

Figure 22, a view taken from the area of final separation of sections of the sample, shows a definite ductile fracture.

Figure 23, a view taken from the center portion of the sample in the branching-pattern area, shows a brittle type of failure occurring in step-wise fashion.

Figure 24 presents a view taken from the area of fracture initiation, where the fracture is intergranular, with inclusions in the fracture domains.

E. 18%-NICKEL MARAGING STEEL

The two 18%-nickel maraging steel samples studied are shown sketched in Figure 19. One was in the cold-worked and aged condition (Group I-3), and the other in the annealed and aged condition (I-1). The cold worked material failed in 626 hours in distilled water, the annealed and aged in 100 hours in 0.25% sodium dichromate.

Figure 25 shows a typical view of a fracture on the cold worked material. This fractograph seems to illustrate a brittle stepwise fracture along vaguely outlined domains.

Figure 26 shows a typical view of a fracture in the annealed and maraged material. This view shows an excellent example of pure brittle fracture. The modeling effect shown in the upper right hand portion of the fractograph is probably due to body-centered-cubic precipitates in the grain structure.

Figure 27 shows another view of the fracture surface of the annealed and maraged material. The dimpled effect is caused by glide decohesion striations in an essentially brittle fracture. In this area of the fracture the mode is beginning to change from purely the brittle to the ductile.

V. SUMMARY AND CONCLUSIONS

Based on the results of the tests during the one year contract, the following conclusions are drawn.

A. The 6Al-4V Titanium alloy shows complete immunity to stress corrosion failure under the conditions of the test program.

B. Both the 18% and 20% grades of maraging steel show significant susceptibility to stress corrosion failure.

C. The maraging steels tested show the following approximate order of (decreasing) susceptibility to stress corrosion failure. (Remnant material given limited testing is omitted).

1. Welded 20% nickel
2. Annealed 20% nickel
3. Annealed 18% nickel (0.62% Ti)
4. Welded 18% nickel (0.50% Ti)
5. Annealed 18% nickel (0.50% Ti)
6. Cold reduced 18% nickel (0.62% Ti)
7. Cold reduced 18% nickel (0.50% Ti)
8. Cold reduced 20% nickel

D. The environments employed in this program indicate the following approximate (decreasing) order of aggressiveness in causing stress corrosion failure of maraging steels.

1. Natural seawater immersion
2. 140°F water-saturated air
3. Aerated 3% NaCl solution
4. Aerated distilled water
5. Kure Beach 50-ft lot atmosphere
6. Bayonne, N.J., industrial atmosphere
7. Newport Beach atmosphere
8. Aerated tap water
9. 0.25% sodium dichromate solution
10. 4% soluble oil (18%-nickel-grade only)
11. Trichloroethylene
12. Cosmoline (no failures)
13. Laboratory air (no failures)

E. The cracking of the annealed and maraged material is found to be intergranular. Cracking in material that has undergone cold deformation prior to maraging is found to be transgranular with cracks at acute angles to the specimen surface.

F. Welded samples show a tendency to preferential failure in the heat-affected zone.

G. Limited testing of vacuum melted 9Ni-4Co steel shows that it also is susceptible to stress corrosion failure.

H. No single coating was found that will prevent stress corrosion cracking of H-11 steel when tempered in the susceptible region. Zinc-based coatings prevented failure in atmospheric environments but failed rapidly in salt water immersion. Conversely, chromate bearing coatings prevented stress-corrosion cracking in the salt water immersion but failed in long term atmospheric exposure. However, based upon overall performance, the following order is established.

1. Inhibited epoxy 454-1-1
2. Inhibited epoxy 463-1-5
3. Vinyl, AM-33
4. Polyurethane, X-500
5. Inorganic zinc, Type 11

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TABLE 1

MASTER PLAN, BENT-BEAM STRESS-CORROSION TESTS

Alloy	Processing Condition (Titanium Content of Maraging Steel Shown)	Strength Level, 0.2% Offset Yield (psi)	Specimen Code	Test Environments: Distilled Water	Tap Water	3% NaCl Solution	0.2% Sodium Dichromate Solution	4% Soluble Oil Solution	High Humidity	Trichloro-ethylene	Cosmoline	Ambient Air	Sea Coast Atmosphere
6Al-4V titanium	Annealed	138,000	G-1	3*	3	3	3	3	3	3	3	-	3
	Quenched and Aged	163,000	G-2	3	3	3	3	3	3	3	3	-	3
	Welded	135,000	G-W	2	2	2	2	2	2	2	2	2	2
	Total			8	8	8	8	8	8	8	8	2	8
20%-Nickel Maraging Steel	Annealed and Aged	291,000	H-1	3	3	3	3	3	3	3	3	3	3
	50% CW and Aged	321,000	H-2	3	3	3	3	3	3	3	3	3	3
	75% CW and Aged	298,300	H-3	3	3	3	3	3	3	3	3	3	3
	Welded and Aged	245,000	H-W	3	3	3	3	3	3	3	3	3	3
	Total			12	12	12	12	12	12	12	12	12	12
18-Nickel Maraging Steel	Annealed & Aged (0.62% Ti)	283,000	I-1	3	3	3	3	3	3	3	3	3	3
	50% CW & Aged (0.50% Ti)	302,400	I-2	3	3	3	3	3	3	3	3	3	3
	50% CW & Aged (0.62% Ti)	323,000	I-3	3	3	3	3	3	3	3	3	3	3
	Annealed & Aged (0.50% Ti)	249,900	I-4	3	3	3	3	3	3	3	3	3	3
	50% CW & Aged (0.40% Ti)	278,000	I-5	3	-	2	-	-	3	-	-	1	2
	Annealed & Aged (0.52% Ti)	255,400	I-6	3	-	2	-	-	3	-	-	2	3
	50% CW & Aged (0.52% Ti)	331,000	I-7	3	-	2	-	-	3	-	-	2	3
	Annealed & Aged (1.00% Ti)	323,200	I-8	3	-	2	-	-	3	-	-	1	2
	50% CW & Aged (1.00 Ti)	354,400	I-9	3	-	2	-	-	3	-	-	2	2
	Welded & Aged (0.50% Ti)	236,600	I-W	3	3	3	3	3	3	3	3	3	3
	Total			30	15	25	15	15	30	15	15	25	27
9 Ni-4 Co** Vacuum-Cast Alloy	Aged (0.25-0.30% C)		J-1	3	3	3	3	3	3	3	3	3	3
	Aged (0.40-0.45% C)		J-2	3	3	3	3	3	3	3	3	3	3
	Total			6	6	6	6	6	6	6	6	6	6
H-11 Steel (Coating Tests)	Application of Various Protective Coatings			-	-	37	-	-	29	-	-	-	26
	Total			56	41	86	41	41	85	41	41	45	79

* Number of replicate tests conducted.

** Test schedule of 9Ni-4Co alloy revised due to late delivery.

TABLE 2

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES
OF 6-Al-4V TITANIUM

	Chemical Analysis,* %								
	C	Al	V	O_2	N_2	H_2	Ti	Fe	Other
Aerojet analysis	0.3	6.1	4.1	0.083	0.014	80 ppm	Bal	0.16	0.18

	Mechanical Properties (Transverse)				
Treatment and Testing	Yield Strength (0.2% Offset) psi	Ultimate Strength psi	Elon-gation %	R_c Hard-ness	Crack Growth Energy, Gc_2** in.-lb/in.^{2}
Annealed					
Mill report	131,900	141,400	12	33.5	440
Aerojet test	138,000	143,800	14	34	
1675°F for 1 hour, W.Q. aged 900°F for 8 hour, then Aerojet test	162,700	176,800	7	38.5	450
Welded, then Aerojet test	131,500**	135,200	9.5	33.0	

*Titanium Metals Corporation HT 4141.

**Tensile failures in parent metal.

TABLE 3

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF MARAGING STEELS

Supplier	Heat No.	Mill-Certified Analysis, % C	Mn	P	S	Si	Ni	Co	Mo	Al	Cb	Cr	Zr	Ti	Ca	B
Allegheny-Ludlum	W-24254	0.009	0.09	0.002	0.005	0.06	20.41	--	-	0.29	0.39	-	0.002	1.40	0.004	0.003
	W-24178	0.012	0.01	0.003	0.005	0.01	18.69	8.90	4.92	0.029	-	-	0.003	0.62	0.006	0.002
	477	0.018	0.002	0.006	0.004	0.024	18.29	9.10	4.95	0.089	-	-	<0.004	0.40	<0.0006	<0.003
	448	0.029	0.002	0.004	0.008	0.009	18.51	8.48	4.92	0.089	-	-	<0.004	0.52	<0.0006	<0.003
Allegheny-Ludlum	476	0.020	0.002	0.006	0.005	0.014	18.60	9.05	4.90	0.078	-	-	<0.004	1.00	<0.0006	<0.003
Republic Steel	3960502	0.020	0.08	0.007	0.006	0.15	18.48	7.00	4.84	0.21	-	0.10	0.035	0.50	Added	0.0036

Heat No.	Prior Condition	Aging Treatment	Table 1 Code No.	Transverse Mechanical Properties (Aerojet Tests) 0.2%-Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	% Elongation in 2 in.	Reduction in Area, %	Crack-Growth Energy (G_c), in.-lb/in.^{2}	R_c Hardness
W-24254	Annealed	none	-	128.5	170.7	7.5	53	-	34
	Annealed	-100°F +850°F 4 hr	H-1	291.3	302.2	3	17	58.3	54
	50% CW	none	-	184.0	201.6	5	50	-	39
	50% CW	850°F 4 hr	H-2	321.0	327.1	3	25	22.7	55.5
	75% CW	none	-	205.7	220.9	6	46	-	44
	75% CW	850°F 4 hr	H-3	298.3	308.8	2.5	13	15.7	55
	Welded	none	-	124.4	146.7	3.5	25	-	-
W-24254	Welded	-100°F +850°F 4 hr	H-W	245.0	252.0	1.5	5	-	-
W-24178	Annealed*	none	-	102.0	153.3	14.8	62	-	30.5
	Annealed*	900°F 3 hr	I-1	283.0	294.0	8	38	552.0	53.5
	50% CW	none	-	167.7	189.0	3.5	51	-	36.5
W-24178	50% CW	900°F 3 hr	I-3	323.8	328.4	1.5	28	220.0	55
477	50% CW	none	-	169.3	196.9	6.5	40	-	38.5
477	50% CW	900°F 3 hr	I-5	278.0	280.7	2	8	435.0	55.0
448	Annealed	none	-	105.3	150.3	10	45	-	30.5
	Annealed	900°F 3 hr	I-6	255.4	265.9	5	9	634.0	52
	50% CW	none	-	175.5	199.8	4.5	47.5	-	38
448	50% CW	900°F 3 hr	I-7	331.0	332.5	1.5	7	525.0	55
476	Annealed	none	-	128.3	174.7	5.5	48	-	36
	Annealed	900°F 3 hr	I-8	323.3	330.0	2.5	27	402.0	56
	50% CW	none	-	192.2	217.0	2.5	40	-	41
476	50% CW	900°F 3 hr	I-9	354.4	354.9	1	1.5	156.5	58
3960502	Annealed	none	-	119.5	143.5	7	55	-	29.5
	Annealed	900°F 3 hr	I-4	249.9	254.7	4	37	670.0	50.5
	50% CW	none	-	166.2	182.9	5.5	58.5	-	35.5
	50% CW	900°F 3 hr	I-2	302.5	308.1	4	26	321.0	52.5
	Welded	none	-	124.5	145.0	4.5	47	-	-
3960502	Welded	900°F 3 hr	I-W	236.6	242.0	2	20	-	-

*Material received in the 50% cold-worked condition and annealed at 1500°F in the laboratory.

TABLE 4

PROPERTIES OF VACUUM-CAST 9Ni-4Co STEEL

Mill Certified Chemical Analysis*

C	Mn	P	S	Si	Co	Ni	Cr	Mo	V
0.30	0.23	0.006	0.007	0.02	4.10	8.65	0.43	0.35	0.10

Mechanical Properties (Transverse) Aerojet Tests

Condition	Yield Strength (0.2% Offset) ksi	Ultimate Tensile Strength ksi	Elongation %	% Reduction of Area	Rc Hardness
(Austenitized 1550°F in argon - oil quenched 2 hours double temper at temperatures shown)					
400°F	190.3	230.3	8	52	48
600°F	184.6	203.0	7	54	43
800°F	172.4	186.7	9	59	41
1000°F	176.7	187.1	11	60	40.5

*Republic Heat 3950924

TABLE 5

TAP-WATER ANALYSIS

Analysis of Dissolved Solids	Parts per Million	Hypothetical Combinations of Dissolved Solids	Parts per Million	Other Characteristics	Determinations
Silica	13.8	Silica	13.8	Specific conductance, micromhos/cm	355
Aluminum oxide	Trace	Aluminum oxide	Trace	Hydrogen-ion concentration, pH	7.7
Iron oxide	Trace	Iron oxide	Trace	Boron (B), ppm	None
Calcium	56.1	Calcium bicarbonate	226.9	Fluoride (F), ppm	0.2
Magnesium	10.7	Calcium sulfate	None	Langelier index	ND*
Sodium	15.4	Calcium chloride	None	Turbidity	None
Sulfate	14.0	Magnesium bicarbonate	64.4	Color	10
Chloride	8.0	Magnesium sulfate	None	Odor	None
Carbonate	None	Magnesium chloride	None	Taste	ND*
Bicarbonate	231.9	Sodium bicarbonate	10.1	Suspended matter	None
Nitrate	1.8	Sodium carbonate	None		
Nitrate	ND*	Sodium sulfate	20.6		
Borate	None	Sodium chloride	13.4		
		Sodium nitrate	2.5		
		Sodium nitrite	ND*		
Total solids	351.7	Total solids	351.7		
Total non-volatile solids	233.8	Total hardness as $CaCO_3$	184		

*ND, not detected

TABLE 6

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF MARAGING STEEL
SAMPLES FURNISHED BY INTERNATIONAL NICKEL COMPANY

Supplier	Heat No.	Reported Chemical Analysis, %											
		C	Mn	P	S	Si	Ni	Co	Mo	Al	Zr	Ti	B
Vanadium Alloys	A6939	.014	.08	.002	.002	.096	17.85	7.40	4.55	.051	.01	0.35	.0023
Allegheny Ludlum	23832	.021	.02	.005	.002	.03	18.50	7.32	5.05	0.13	.01	0.41	.0014
Allegheny Ludlum	23831	.019	.02	.004	.002	.04	18.87	8.72	4.65	0.17	.01	0.67	.0015

Heat No.	Heat Treatment	Code No.	Longitudinal Mechanical Properties (INCO Tests)			
			0.2% Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	% Elongation in 2 in.	Hardness, Rc
A6939	1500°F, 15 min; AC, 900°F, 3 hr, AC	INCO-2	262.8	267.4	4.2	50
23832	1500°F, 35 min; AC, 900°F, 3 hr, AC	INCO-3	279.9	280.6	3.5	52
23831	1500°F, 35 min; AC, 900°F, 3 hr, AC	INCO-4	303.1	305.6	3.2	55

TABLE 7

DIMENSIONS AND SURFACE CONDITION OF BENT-BEAM SPECIMENS

Code No.	Dimensions, in. Thickness	Width	Length	Final Surface Preparation
G-1	0.059	15/16	7.470	Surface ground
G-2	0.059		7.692	Surface ground
G-W	0.085		7.400	Vapor blasted
H-1	0.082		7.322	Hand sanded
H-2	0.078		7.458	Vapor blasted
H-3	0.082		7.349	Hand sanded
H-W	0.082		7.221	Vapor blasted
I-1	0.078		7.348	Hand sanded
I-2	0.081		7.403	Vapor blasted
I-3	0.078		7.484	Hand sanded
I-4	0.076	15/16	7.304	Vapor blasted
I-5	0.064	3/8	7.653	Hand sanded
I-6	0.064		7.419	
I-7	0.064		7.804	
I-8	0.064		7.753	
I-9	0.064	3/8	7.983	Hand sanded
I-W	0.076	15/16	7.242	Vapor blasted
J-1	0.078		7.121	
J-2	0.078		7.137	
J-3	0.078	15/16	7.147	Vapor blasted
INCO-2	0.050	1.0	7.900	Surface ground
INCO-3	0.050	1.0	7.58, 8.28	Surface ground
INCO-4	0.050	1.0	7.55, 8.26	Surface ground
INCO-4	0.075	1.0	7.73	Surface ground

TABLE 8

AERATED-DISTILLED-WATER, BENT-BEAM, STRESS-CORROSION TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	11	10.2-18
↓	50% CW & aged	H-2	321.0	1/3	330	330-NF2900
↓	75% CW & aged	H-3	293.3	3/3	2918	1284-3450
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	83	23-200
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	68	50-85
↓	↓	I-6	255.4	0/3	-	NF3600
↓	↓	I-1	283.0	3/3	34.5	20.5-46.5
↓	Annealed & aged	I-8	323.2	3/3	24	20-27.5
↓	50% CW & aged	I-5	278.0	0/3	-	NF3600
↓	↓	I-2	302.5	3/3	1420	1130-1900
↓	↓	I-7	331.0	0/3	-	NF3600
↓	↓	I-3	323.0	4/4	625	440-988
↓	50% CW & aged	I-9	354.4	1/3	668	668-NF3600
18%-Ni maraging steel	Welded & aged	I-W	236.6	3/3	343	310-360
9%-Ni-4% Co steel	800°F temper	J-1	172.4	0/3	-	NF1400
	600°F temper	J-2	184.6	0/3	-	NF1400
9%-Ni-4% Co steel	400°F temper	J-3	190.3	2/3	1280	1150-NF1400

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 9

AERATED-TAP-WATER, BENT-BEAM, STRESS-CORROSION TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/3	-	NF3100
	50% CW & aged	H-2	321.0	1/3	2610	2610-NF2900
	75% CW & aged	H-3	298.3	2/3	1955	1510-NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	5.2	3.3-6.5
18%-Ni maraging steel	Annealed & aged	I-4	249.9	1/3	1920	1920-NF2450
	Annealed & aged	I-1	283.0	3/3	1830	325-4800
	50% CW & aged	I-2	302.5	0/3	-	NF2200
	50% CW & aged	I-3	323.0	0/3	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	3/3	1270	623-1895
9%-Ni-4% Co steel	800°F temper	J-1	172.4	0/3	-	NF1400
9%-Ni-4% Co steel	600°F temper	J-2	184.6	0/3	-	NF1400
9%-Ni-4% Co steel	400°F temper	J-3	190.3	0/3	-	NF1400

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 10

AERATED-SALT-WATER, BENT-BEAM, STRESS CORROSION TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	7.3	6-8.5
	50% CW & aged	H-2	321.0	0/3	-	NF2900
	75% CW & aged	H-3	298.3	0/3	-	NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	0.8	0.75-0.85
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	430	140-700
		I-6	255.4	0/2	-	NF3600
		I-1	283.0	3/3	51.5	19-100
	Annealed & aged	I-8	323.2	2/2	6.5	6-7
	50% CW & aged	I-5	278.0	0/2	-	NF3600
		I-2	302.5	0/3	-	NF2300
		I-7	331.0	0/2	-	NF3600
		I-3	323.0	3/3	1930	1000-3200
	50% CW & aged	I-9	254.4	2/2	20	20-20
	Welded & aged	I-W	236.6	4/4	121	115-139
	INCO-2		262.8	0/2	-	NF1400
	INCO-3		279.9	0/2	-	NF1400
18%-Ni maraging steel	INCO-4		303.1	0/3	-	NF1400
9%-Ni 4% Co steel	800°F temper	J-1	172.4	0/3	-	NF1400
	600°F temper	J-2	184.6	0/3	-	NF1400
9%-Ni 4% Co steel	400°F temper	J-3	190.3	0/3	-	NF1400

*All samples were stressed to give a maximum outer-fiber stress of 75° for the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 11

AERATED 0.25% SODIUM DICHROMATE, BENT BEAM, STRESS-CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio***	Failure Time, hours Mean	Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.0	1/3	1.0	1-NF3100
↓	50% CW & aged	H-2	321.0	0/3	-	NF2900
↓	75% CW & aged	H-3	298.3	0/3	-	NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/3	-	NF1950
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF2450
↓	Annealed & aged	I-1	283.0	3/3	117	100-150
↓	50% CW & aged	I-2	320.5	0/3	-	NF2200
↓	50% CW & aged	I-3	323.0	0/3	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/3	-	NE1750

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 12

4%-SOLUBLE-OIL SOLUTION
BENT-BEAM, STRESS-CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/2	-	NF2000
↓	50% CW & aged	H-2	321.0	0/3	-	NF2900
↓	75% CW & aged	H-3	298.8	0/3	-	NF2000
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/3	-	NF1950
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	2400****	
↓	Annealed & aged	I-1	283.0	3/3	417	400-450
↓	50% CW & aged	I-2	302.5	0/3	-	NF2200
↓	50% CW & aged	I-3	323.0	0/3	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	3/3	1300	1130-1560

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

****Microcracks noted after 2400 hours exposure; time of initial cracking unknown but cracks undoubtedly developed earlier.

TABLE 13

140°F WATER-SATURATED AIR, BENT-BEAM STRESS CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	100	22-174
	50% CW & aged	H-2	321.0	1/3	1410	1410-NF2900
	75% CW & aged	H-3	298.3	3/3	1200	1080-1860
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	10	1-14
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	370	170-475
		I-6	255.4	3/3	280	212-362
		I-1	283.0	3/3	21	20.5-21.5
	Annealed & aged	I-8	323.2	3/3	56.6	25.5-72
	50% CW & aged	I-5	278.0	0/3	-	NF3600
		I-2	302.5	3/3	380	380-NF400
		I-7	331.0	3/3	-	NF3600
		I-3	232.0	3/3	260	245-290
	50% CW & aged	I-9	354.4	3/3	833	560-1010
18%-Ni maraging steel	Welded & aged	I-W	236.6	3/3	131	115-139
18%-Ni maraging steel	Inco-2		262.8	2/2	1400	1400-1400
9%-Ni-4% Co Steel	800°F Temper	J-1	172.4	0/3	-	NF1400
9%-Ni-4% Co Steel	600°F Temper	J-2	184.6	3/3	725	430-1440
9%-Ni-4% Co Steel	400°F Temper	J-3	190.3	3/3	184	115-260

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 14

TRICHLOROETHYLENE IMMERSION,
BENT-BEAM STRESS CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF2600
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF2600
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF2600
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	742	500-2200
↓	50% CW & aged	H-2	321.0	1/3	2350	2350-NF2600
↓	75% CW & aged	H-3	293.3	0/3	-	NF2600
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	48	40-68
18%-Ni maraging steel	Annealed & aged	I-1	283.0	3/3	1140	550-2200
↓	50% CW & aged	I-2	302.5	0/3	-	NF1950
↓	50% CW & aged	I-3	323.0	0/3	-	NF2600
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/3	-	NF1750

*All samples were stressed to give maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 15

COSMOLINE IMMERSION, BENT-BEAM STRESS CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/3	-	NF2000
20%-Ni maraging steel	50% CW & aged	H-2	321.0	0/3	-	NF1000
20%-Ni maraging steel	75% CW & aged	H-3	293.3	0/3	-	NF2000
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF500
18%-Ni maraging steel	Annealed & aged	I-1	283.0	0/3	-	NF2000
18%-Ni maraging steel	50% CW & aged	I-3	323.0	0/3	-	NF2000

*All samples were stressed to give maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 16

LABORATORY AIR, BENT-BEAM STRESS CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/0	-	-
6Al-4V titanium	Quenched & aged	G-2	163.0	0/0	-	-
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/3	-	NF3100
↓	50% CW & aged	H-2	321.0	0/2	-	NF2000
↓	75% CW & aged	H-3	293.3	0/3	-	NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/3	-	NF1700
18%-Ni maraging steel	Annealed & aged	I-6	255.4	0/2	-	NF1200
↓	Annealed & aged	I-1	283.0	0/3	-	NF2000
↓	Annealed & aged	I-8	323.2	0/1	-	NF1200
↓	50% CW & aged	I-5	278.0	0/1	-	NF1200
↓	↓	I-7	331.0	0/2	-	NF1200
↓	↓	I-3	323.0	0/3	-	NF2000
↓	50% CW & aged	I-9	354.4	0/2	-	NF1200
18%-Ni maraging steel	Welded & aged	I-W	336.6	0/3	-	NF1500

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 17

SEACOAST EXPOSURE, BENT-BEAM STRESS CORROSION TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF980
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF980
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF980
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	140	115-188
	50% CW & aged	H-2	321.0	3/3	1034	800-1150
	75% CW & aged	H-3	293.3	3/3	1000	860-1150
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	173	100-320
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF1250
		I-6	255.4	0/2	-	NF2900
		I-1	283.0	6/6	380	312-450
	Annealed & aged	I-8	323.2	2/2	700	350-1050
	50% CW & aged	I-5	278.0	0/2	-	NF2900
		I-2	302.5	0/3	-	NE1250
		I-7	331.0	0/2	-	NF2900
		I-3	323.0	0/3	-	NF2900
	50% CW & aged	I-9	354.4	0/2	-	NF2900
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/3	-	NF1250

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 18

RESULTS OF BENT-BEAM STRESS-CORROSION TESTS CONDUCTED ON 18% NICKEL MARAGING STEEL BY INTERNATIONAL NICKEL COMPANY

Alloy Identification	Stress Level	Bayonne Atmosphere (Industrial)		Kure Beach 50-Ft Lot		Harbor Island (Sea Water Immersion)	
		Failed/Tested	Mean, days	Failed/Tested	Mean, days	Failed/Tested	Mean, days
I-4*	75% yield strength	0/2	NF 59*	2/2	28	2/2	1
I-1	75% yield strength	1/2	9	2/2	4	2/2	1
I-2	75% yield strength	0/2	NF 59	0/2	NF 47	2/2	7.5
I-3	75% yield strength	2/2	28	0/2	NF 47	2/2	2.5
I-W	75% yield strength	0/2	NF 1	0/0		0/0	
INCO-2**	150-ksi stress	0/4	NF 314	0/4	NF 291	-	-
	200-ksi stress	0/4	NF 314	0/4	NF 291	-	-
	250-ksi stress	0/4	NF 314***	0/4	NF 291	-	-
INCO-3	150-ksi stress	0/4	NF 314***	0/4	NF 291	-	-
	200-ksi stress	0/4	NF 314***	0/4	NF 291	-	-
	250-ksi stress	0/4	NF 314	0/4	NF 291	-	-
INCO-4	150-ksi stress	0/4	NF 314***	0/4	NF 291	-	-
	200-ksi stress	0/4	NF 314	0/4	NF 291	-	-
	250-ksi stress	0/4	NF 314***	0/4	NF 291	-	-
	300-ksi stress	0/4	NF 314***	4/4	196	-	-

*Code defined in Table 1

**Code defined in Table 2

***Fine cracks reported to be observed on sample surface

TABLE 19

DISTILLED-WATER, CENTER-NOTCH, STRESS-CORROSION TESTS*

Material	Variable	Code No.**	K_c ksi $\sqrt{in.}$	Failure Ratio***	Failure Time Hour Mean	Failure Time Hour Range
6Al-4V titanium	Annealed	G-1	85.0	0/3	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/3	-	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	3/3	5.1	4.6-6.6
20%-Ni maraging steel	75% CW & aged	H-3	20.5	1/3	121	121-NF300
18%-Ni maraging steel	Annealed & aged	I-4	133.0	2/2	62.4	51.4-73.3
↓	Annealed & aged	I-6	129.5	0/1	-	NF200
↓	Annealed & aged	I-1	121.0	3/3	85.3	83-87
↓	50% CW & aged	I-5	107.2	0/1	-	NF200
↓	↓	I-2	92.2	2/2	17.1	16.6-17.6
18%-Ni maraging steel	50% CW & aged	I-3	76.4	2/2	13.2	12.6-13.8

*All samples were given a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 20

3%-SODIUM-CHLORIDE SOLUTION, CENTER-NOTCH, STRESS-CORROSION TESTS*

Material	Variable	Code No.**	K_c ksi $\sqrt{in.}$	Failure Ratio***	Failure Time hours Mean	Failure Time hours Range
6Al-4V titanium	Annealed	G-1	85.0	0/2	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/2	-	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	2/2	7.2	6.6-7.8
20%-Ni maraging steel	50% CW & aged	H-2	24.5	2/2	14.0	8-20
20%-Ni maraging steel	75% CW & aged	H-3	20.5	2/2	40.2	34.4-46
18%-Ni maraging steel	Annealed & aged	I-4	133.0	2/2	12.5	9.5-15.6
		I-6	129.5	3/3	22	10-35
		I-1	121.0	2/2	20.6	18-23
	Annealed & aged	I-8	103.2	2/2	8.8	8.3-9.3
	50% CW & aged	I-5	107.2	2/2	13.4	12.5-14.2
		I-2	92.2	2/2	7.2	7.2-7.2
		I-7	119.0	3/3	9.9	4.4-12.9
		I-3	76.4	2/2	5.9	5.0-6.9
18%-Ni maraging steel	50% CW & aged	I-9	64.4	2/2	4.5	4.0-5.0

*All samples were subjected to a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 21

0.25%-SODIUM-DICHROMATE, CENTER-NOTCH, STRESS-CORROSION TESTS*

Material	Variable	Code No.**	K_c ksi $\sqrt{in.}$	Failure Ratio***	Failure Time hours Mean	Failure Time hours Range
6Al-4V titanium	Annealed	G-1	85.0	0/2	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/2	-	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	0/2	-	NF200
20%-Ni maraging steel	75% CW & aged	H-3	20.5	0/2	-	NF100
18%-Ni maraging steel	Annealed & aged	I-4	133.0	0/1	-	NF100
↓	Annealed & aged	I-1	121.0	1/1	67.9	-
	Annealed & aged	I-8	103.8	1/1	37.7	-
	50% CW & aged	I-5	107.2	0/1	-	NF200
	50% CW & aged	I-7	119.0	0/2	-	NF100
18%-Ni maraging steel	50% CW & aged	I-3	76.4	1/1	33.2	-

*All samples were given a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 22

4%-SOLUBLE-OIL SOLUTION,
CENTER-NOTCH, STRESS-CORROSION TESTS*

Material	Variable	Code No.**	K_c ksi $\sqrt{in.}$	Failure Ratio***	Failure Time hours
6Al-4V titanium	Annealed	G-1	85.0	0/1	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/1	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	0/2	NF200
20%-Ni maraging steel	75% CW & aged	H-3	20.5	0/1	NF100
18%-Ni maraging steel	Annealed & aged	I-4	133.0	0/1	NF100

*All samples were given a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

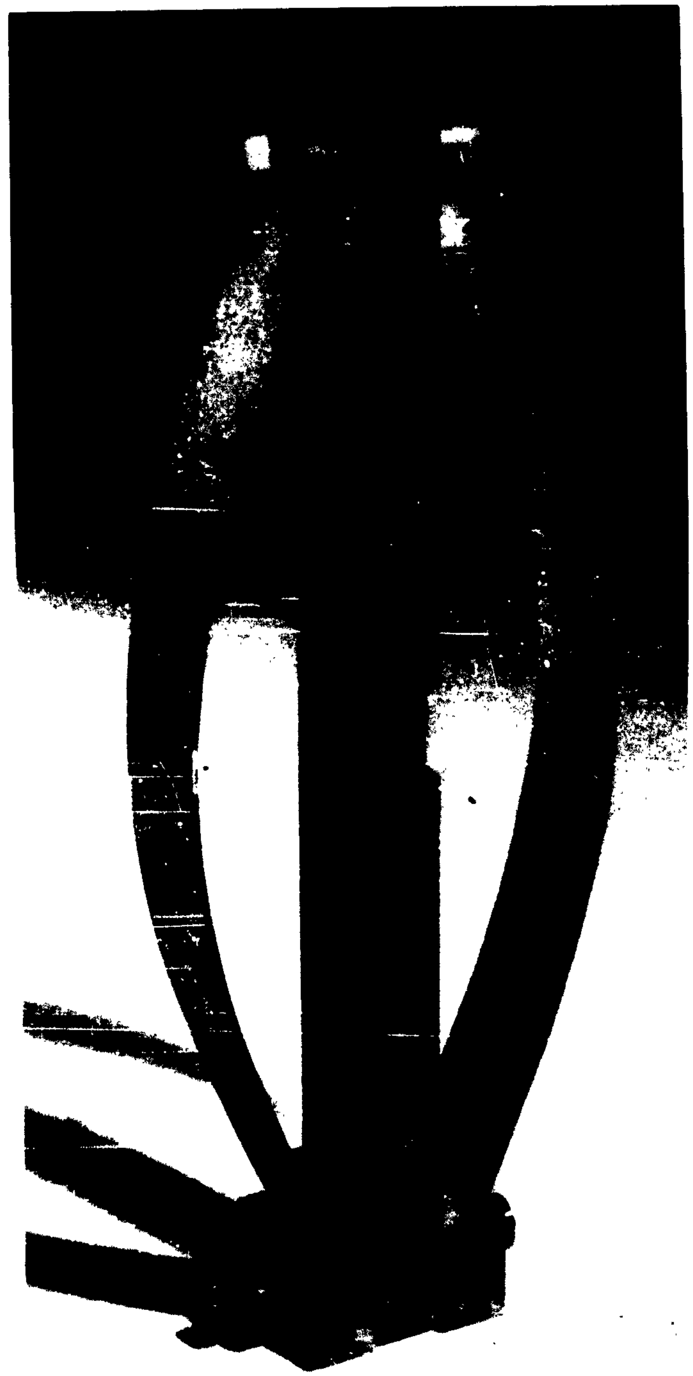
TABLE 23

EVALUATION OF PROTECTIVE COATINGS ON H-11 STEEL (FOR PREVENTION OF STRESS-CORROSION CRACKING)

Base Metal Surface Condition	Coating	Aerated 3% NaCl Solution			140°F Saturated Air			Seacoast Exposure		
		Failure Ratio*	Failure Time, hour		Failure Ratio*	Failure Time, hour		Failure Ratio*	Failure Time, hour	
			Mean	Range		Mean	Range		Mean	Range
Surface ground or sanded	None (control)	4/4	1.6	0.8-2.5	2/2	64	48-70	2/2	116	116-116
	Polyurethane, x-500	3/3**	149	144-168	6/6**	3500	2830-5500	1/2	250	250-NF2900
	Inhibited epoxy 454-1-1	0/2	-	NF3100	3/3**	2720	2590-2850	1/2	1800	1800-NF2900
	Inhibited epoxy 463-1-5	0/3	-	NF3100	3/3	656	400-976	2/2	1820	1630-2010
	Inhibited epoxy 463-4-8	3/3	550	525-578	3/3	845	289-1512	-	-	-
	Epoxy 463-1-5 over 454-1-1	0/4**	-	NF5860	4/4**	4000	2590-4950	-	-	-
	Zinc silicate, Type 4	2/2	1.2	0.8-1.6	2/2	422	147-696	1/2	116	116-NF2900
	80% aluminum epoxy	2/2	1.00	100-100	2/2	30	16-45	2/2	660	550-780
	70% titanium epoxy	2/2	150	140-160	2/2	198	136-256	2/2	910	720-1100
Sand-blasted	None (control)	2/2	18.5	14-23	1/1	26.5	-	1/1	188	-
	Vinyl, AM-33	2/2	3490	3360-3620	1/2	670	670-NF3670	0/2	-	NF2900
	Zinc silicate, Type 4	2/2	14	10-18	0/2	-	NF3670	0/2	-	NF2900
	Epoxy over zinc silicate, Type 4	2/2	77	1.5-153	2/2	513	422-504	0/1	-	NF2900
	Inorganic zinc, Type 11	2/2	687	674-702	2/2	321	723-819	0/4	-	NF2900
	Epoxy 188 over inorganic zinc 11	2/2	54	42-56	0/2	-	NF4270	-	-	-
	Organic zinc XL-4-245	2/2	214	27-400	2/2	766	742-790	-	-	-
	Modified vinyl system	2/2	550	520-583	2/2	640	435-850	2/2	1480	450-2500

*Ratio of number failed to number exposed.

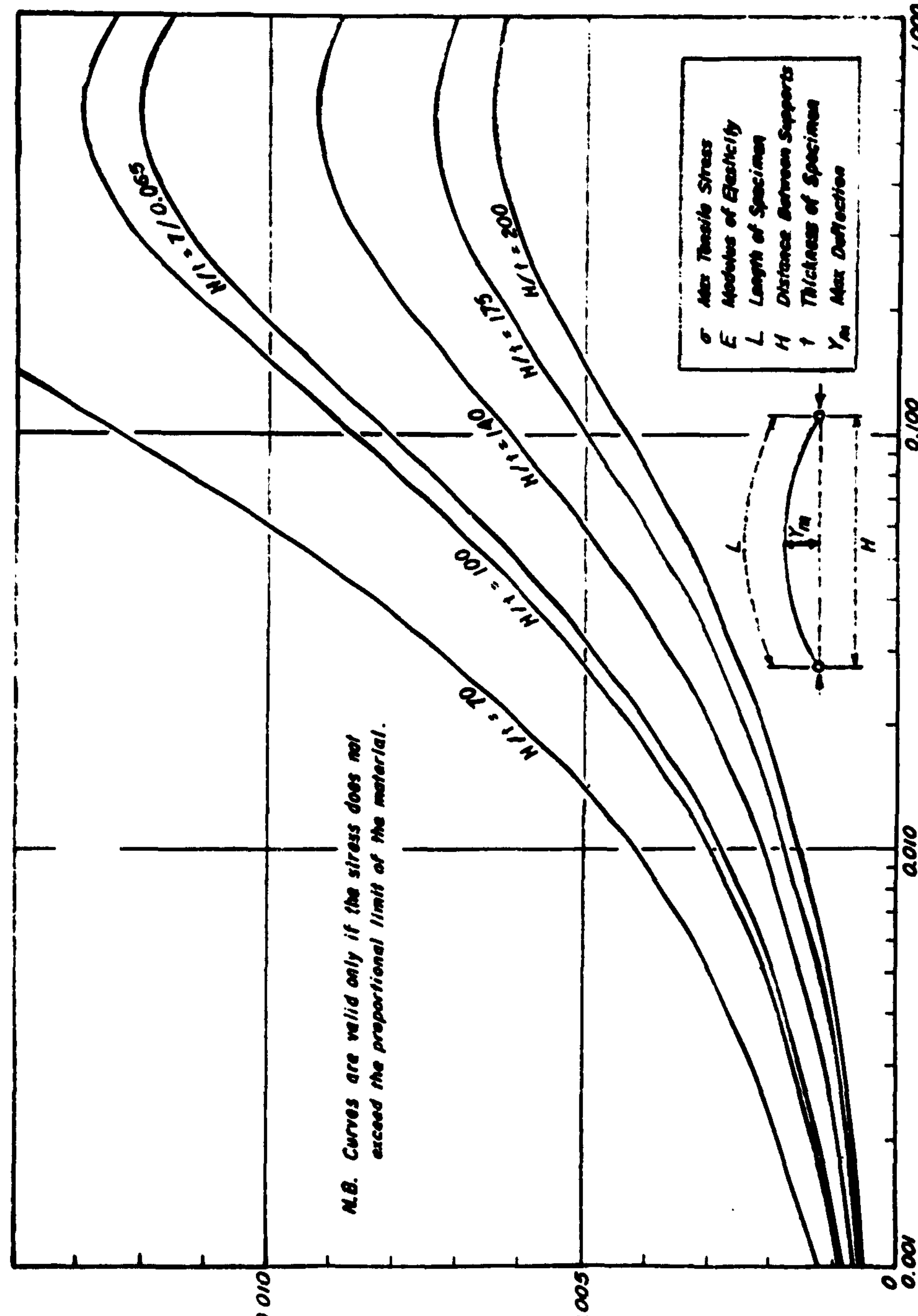
**Data taken from earlier work; samples not in current testing.



1062-616

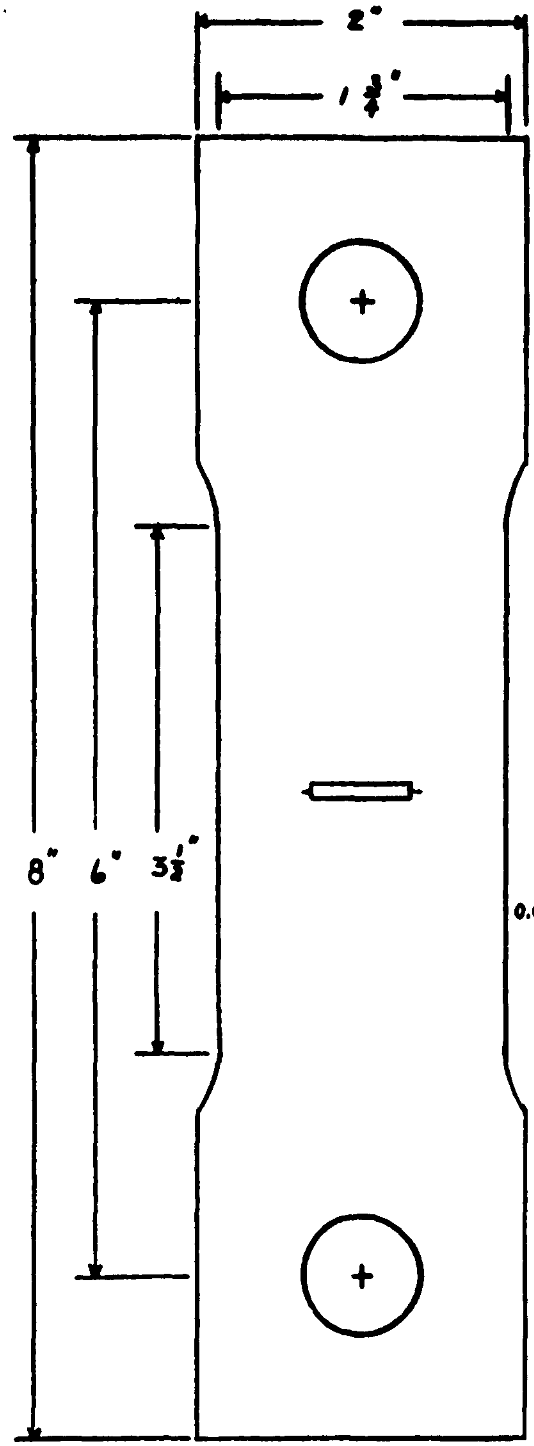
Insulated Bent-Beam Specimens

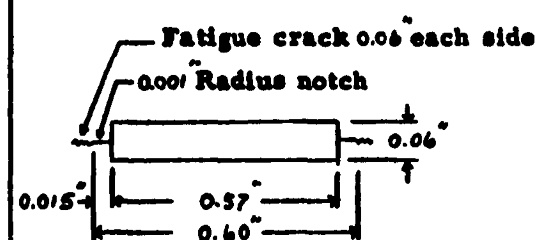
Figure 1



Tensile Stress in Strip Corrosion Specimen

Figure 2

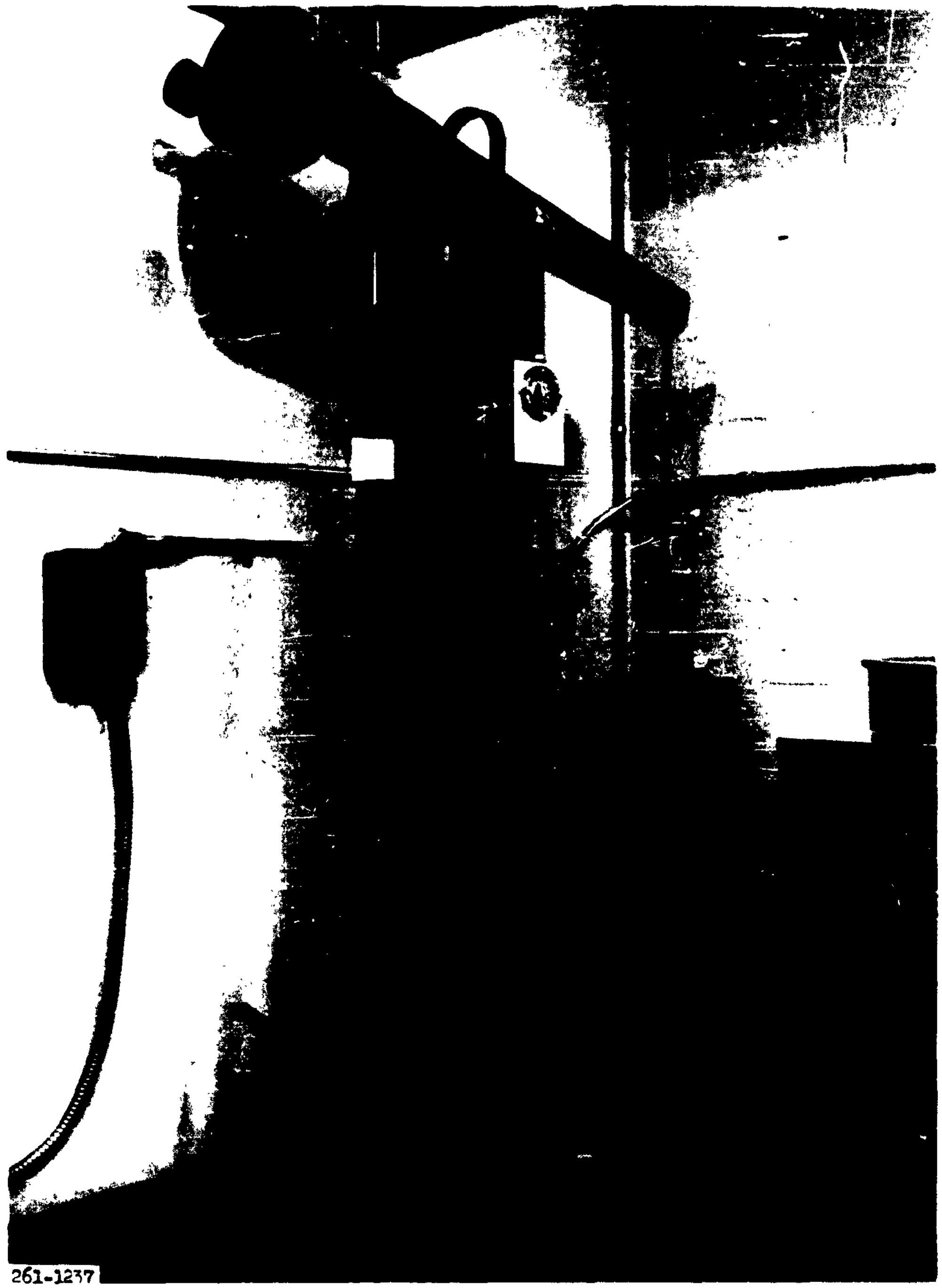




NOTCH DETAIL

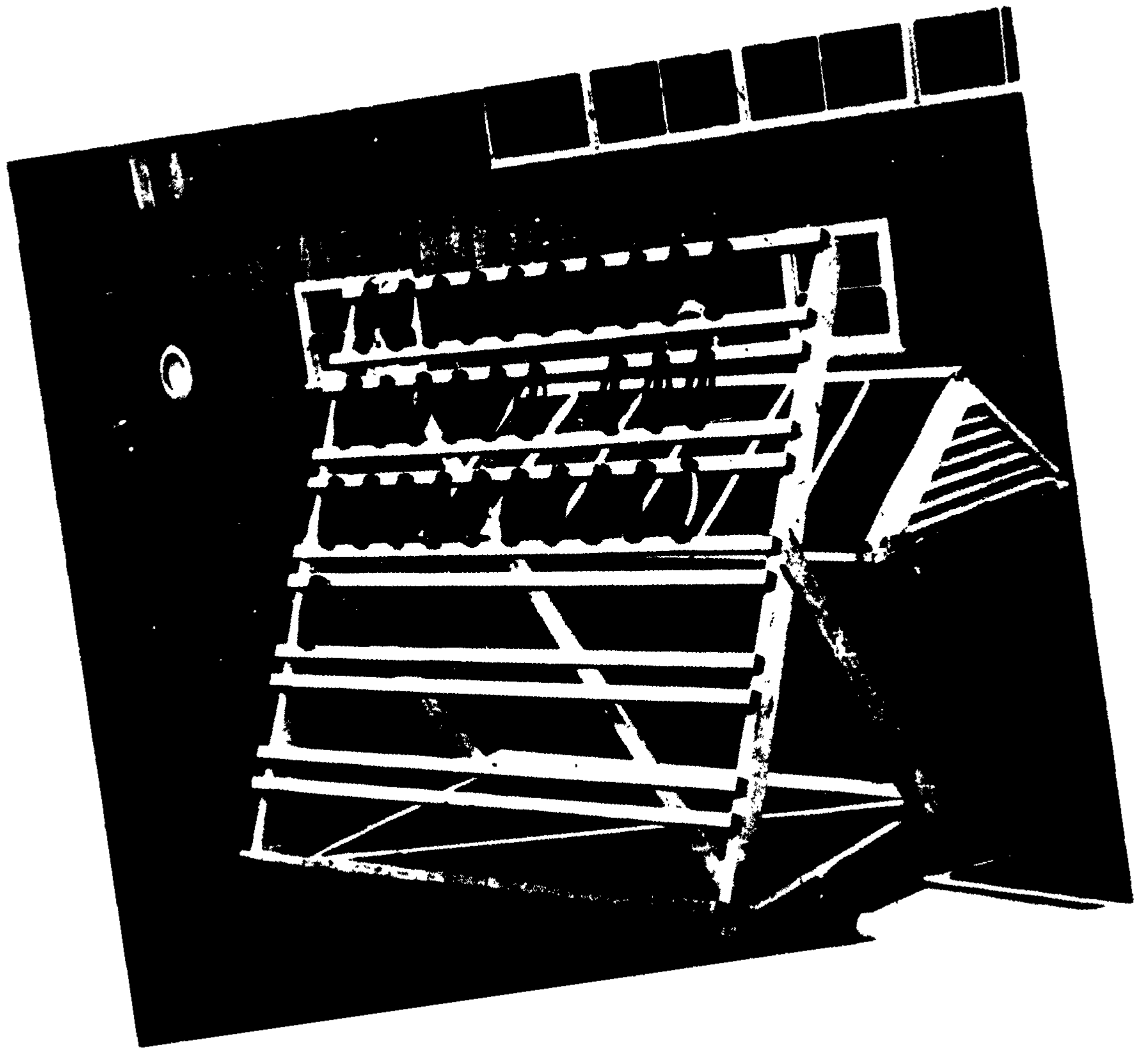
ELOX-NOTCHED SPECIMEN

Figure 3



Stress-Corrosion Test Setup for Center-Notched Specimens

Figure 4



Seacoast-Exposure Test Rack

Figure 5

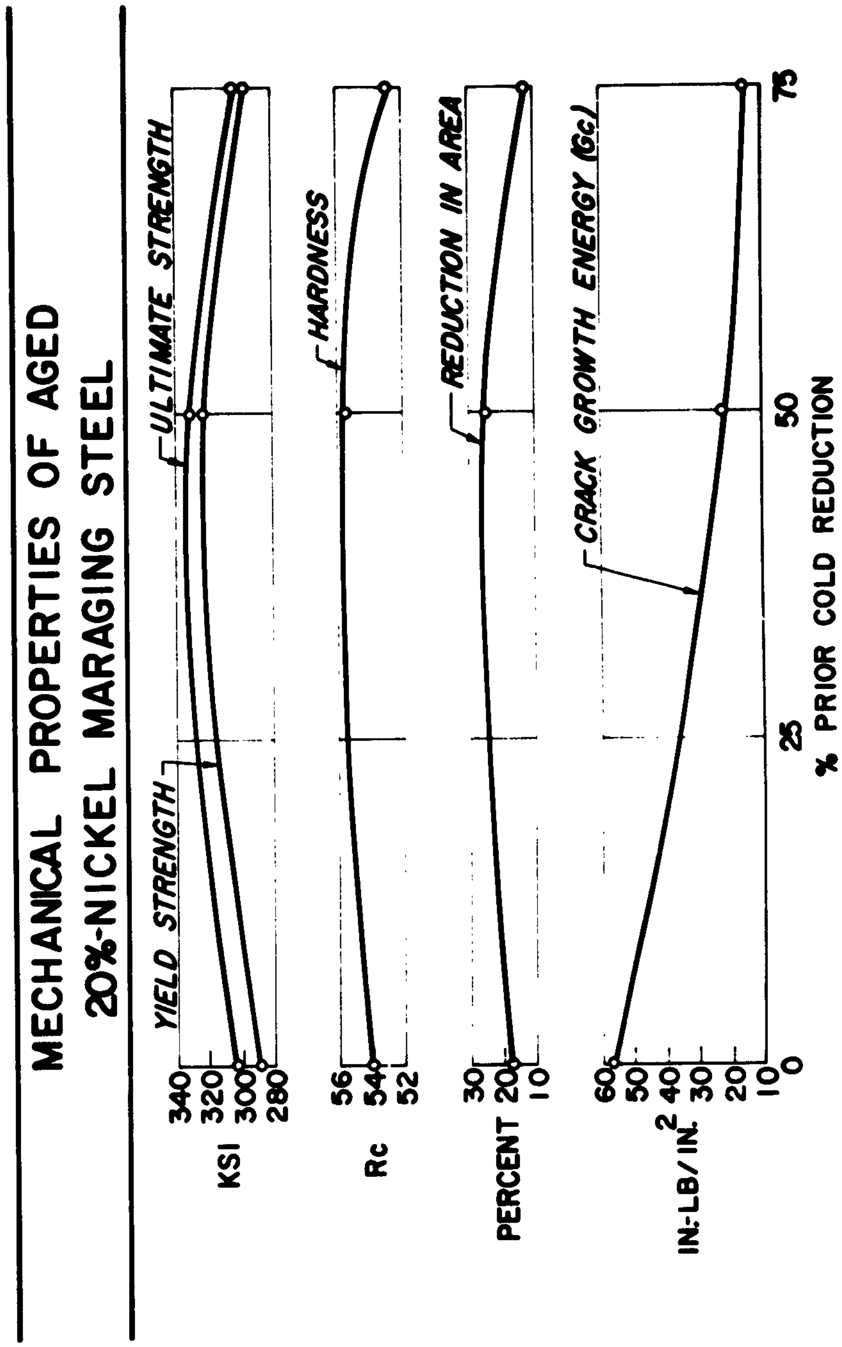

MECHANICAL PROPERTIES OF AGED
20%-NICKEL MARAGING STEEL
ULTIMATE STRENGTH
YIELD STRENGTH
KSI
340
320
300
280
HARDNESS
Rc
56
54
52
REDUCTION IN AREA
PERCENT
30
20
10
CRACK GROWTH ENERGY (Gc)
IN-LB/IN.2
60
50
40
30
20
10
0
0
25
50
75
% PRIOR COLD REDUCTION

Figure 6

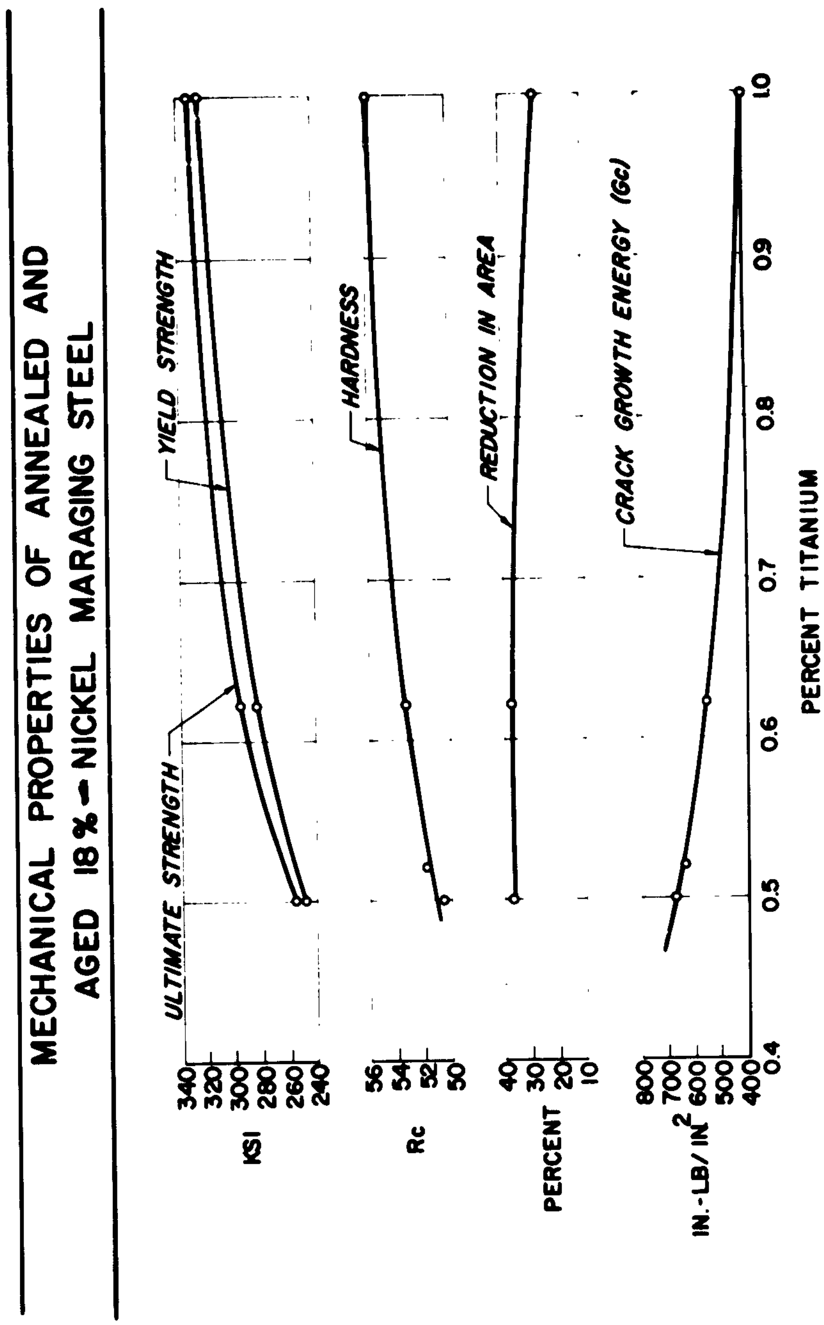

MECHANICAL PROPERTIES OF ANNEALED AND AGED 18% NICKEL MARAGING STEEL
ULTIMATE STRENGTH
YIELD STRENGTH
HARDNESS
REDUCTION IN AREA
CRACK GROWTH ENERGY (Gc)
KSI
340
320
300
280
260
240
Rc
56
54
52
50
PERCENT
40
30
20
10
IN.-LB/ IN²
800
700
600
500
400
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PERCENT TITANIUM

Figure 7

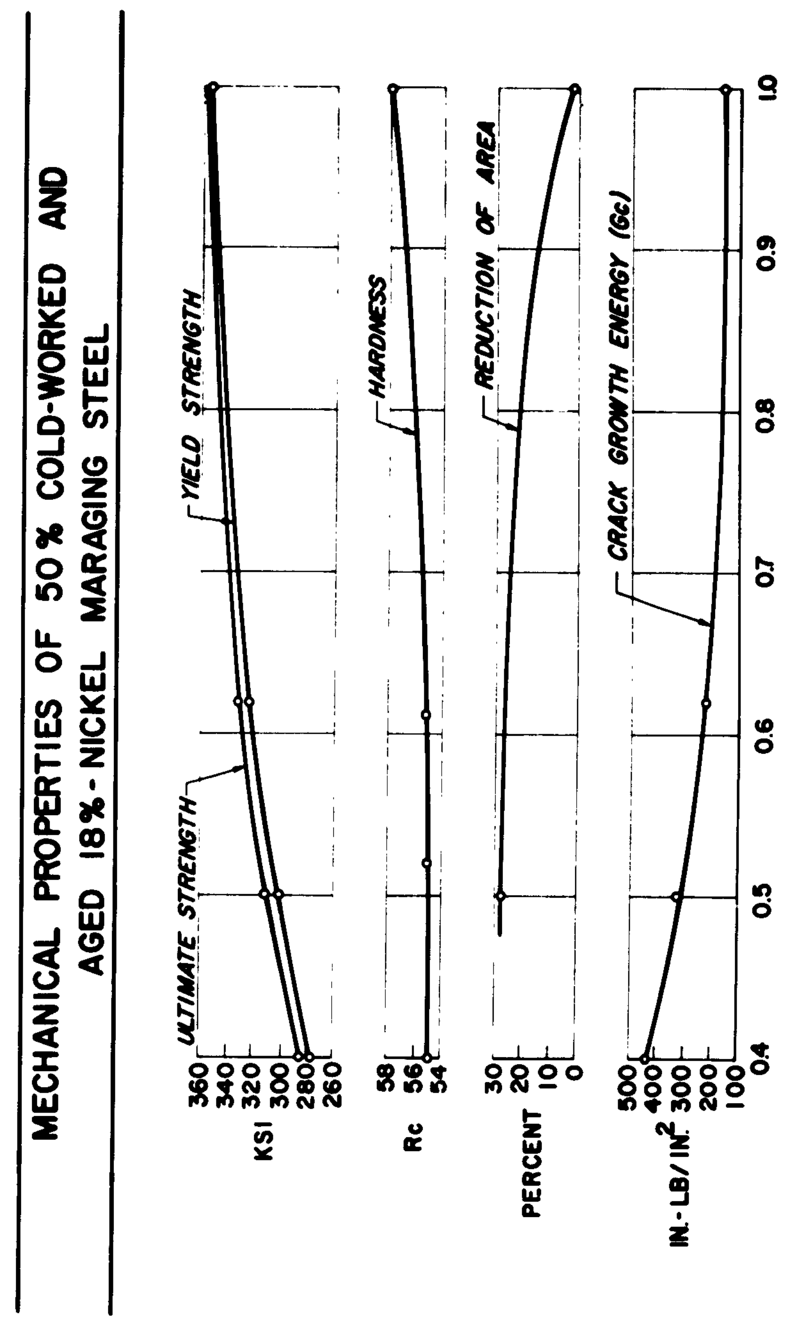
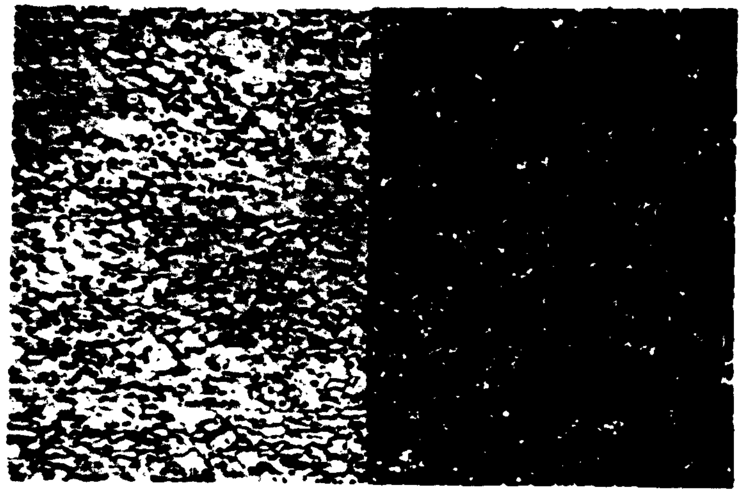
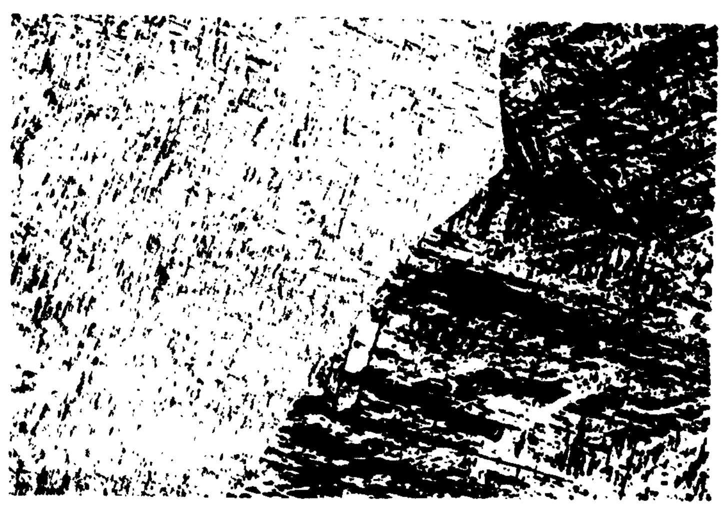

MECHANICAL PROPERTIES OF 50% COLD-WORKED AND
AGED 18%-NICKEL MARAGING STEEL
ULTIMATE STRENGTH
YIELD STRENGTH
HARDNESS
REDUCTION OF AREA
CRACK GROWTH ENERGY (Gc)
KSI
360
340
320
300
280
260
Rc
58
56
54
PERCENT
30
20
10
0
IN.-LB/IN.²
500
400
300
200
100
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PERCENT TITANIUM

Figure 8



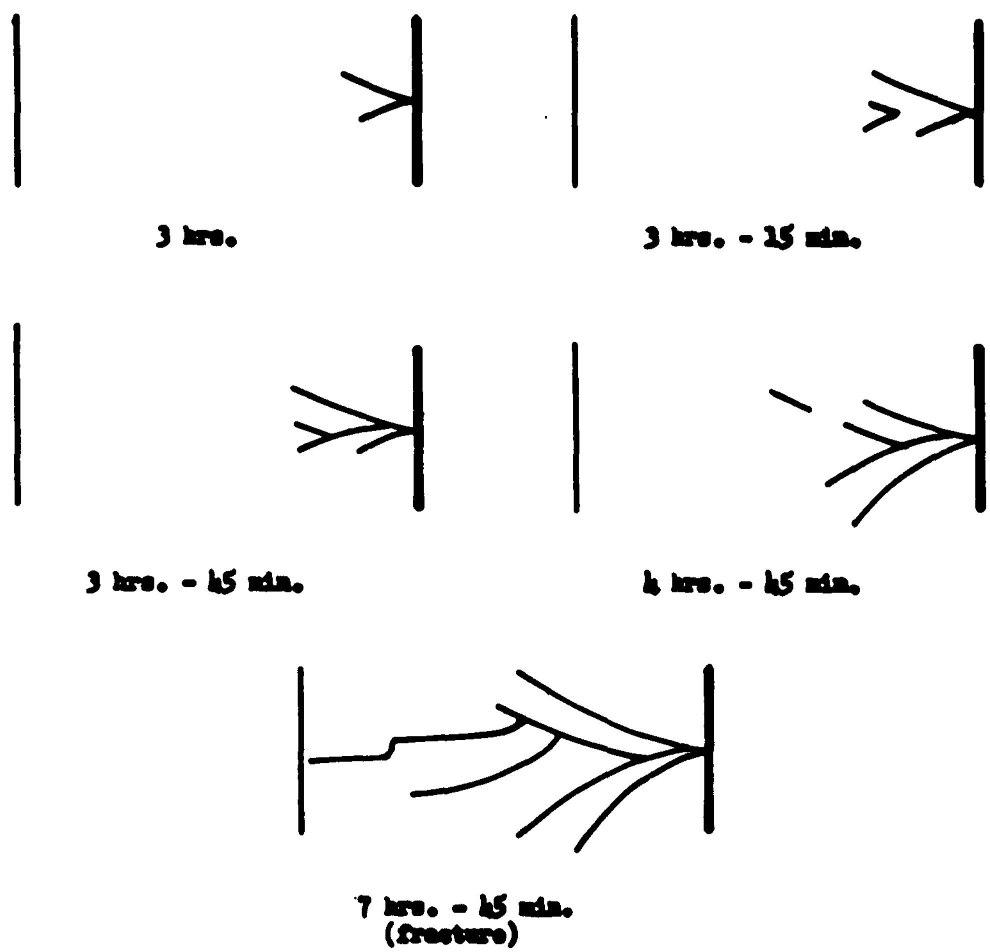
Microstructure of Annealed and Aged 6Al-4V Titanium Alloy (Group G-1). Left portion was taken with bright field, right with polarized light to show alpha-beta structure. Etchant Krolls, (500X)



Microstructure of Weld Zone on Above Alloy. Left area is weld metal. Right is weld heat-affected-zone. Etchant Krolls (100X)

General Microstructure of 6Al-4U Titanium Alloy

Figure 9



Crack Propagation Study on 20%-Nickel Maraging Steel in Salt Water

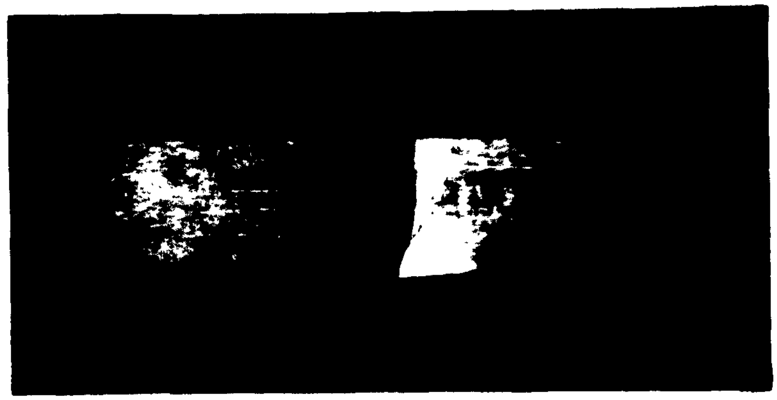
Figure 10

Crack Pattern on Surface of Beam Sample after 10 hours in Aerated Distilled Water. (5X)

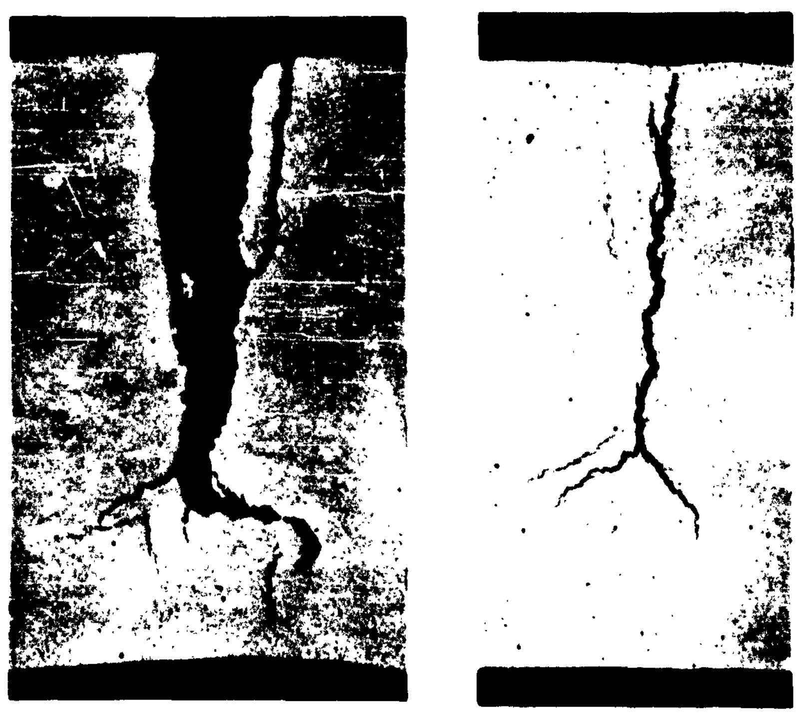
Vertical View of Cracking in Above Sample Showing Intergranular Cracks. Etchant is Diluted Marbles Reagent (1000X)

Stress-Corrosion Crack Pattern on 20%-Nickel Maraging Steel

Figure 11



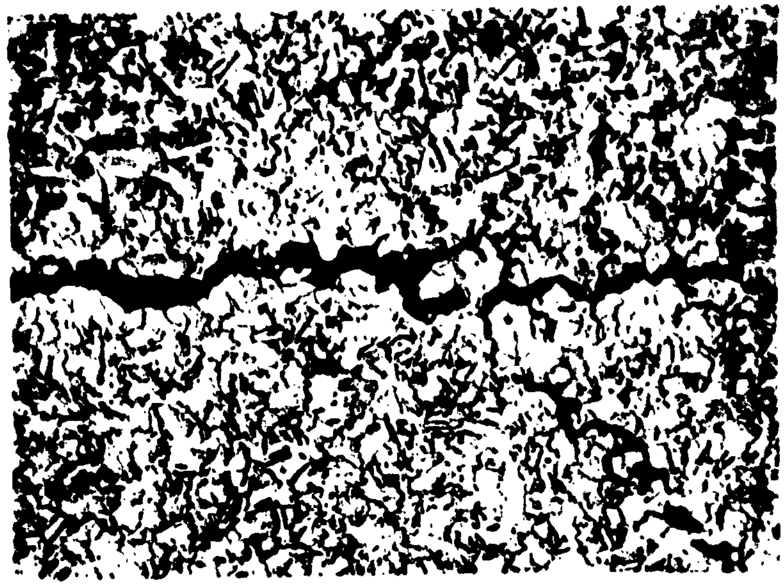
Surface of Annealed-and-Aged 18%-Nickel Maraging Steel Cracked in Chromate Solution (Approx. 1X)



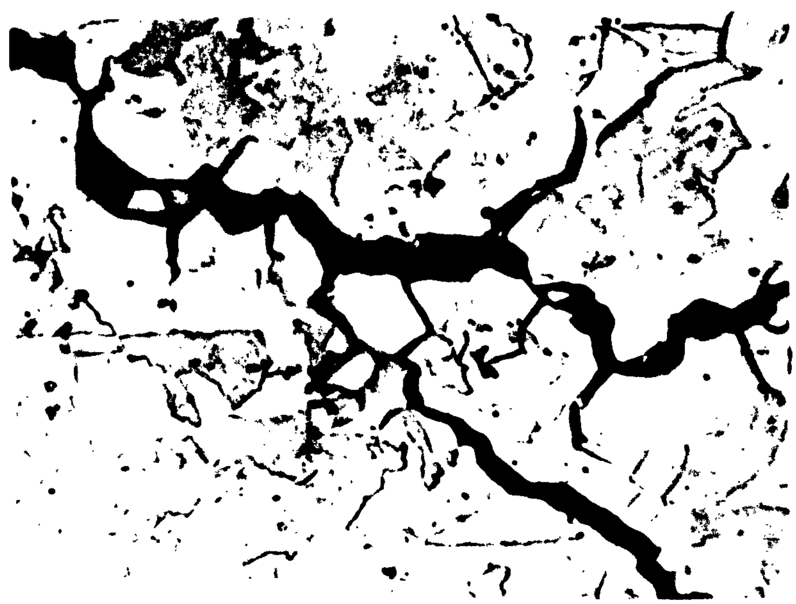
Longitudinal Section Through Cracked Area Showing Main Crack (left) and Branch Crack (right) (50X)

Stress-Corrosion-Crack Pattern in 18%-Nickel Maraging Steel (I-1)

Figure 12



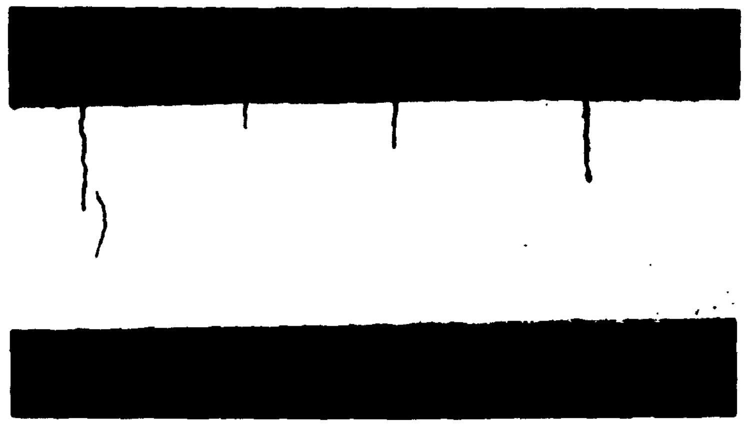
Vertical Section of Failed Annealed-and-Aged 18%-Nickel Maraging Steel Specimen Showing Intergranular Cracks. Marbles Etch (250X)



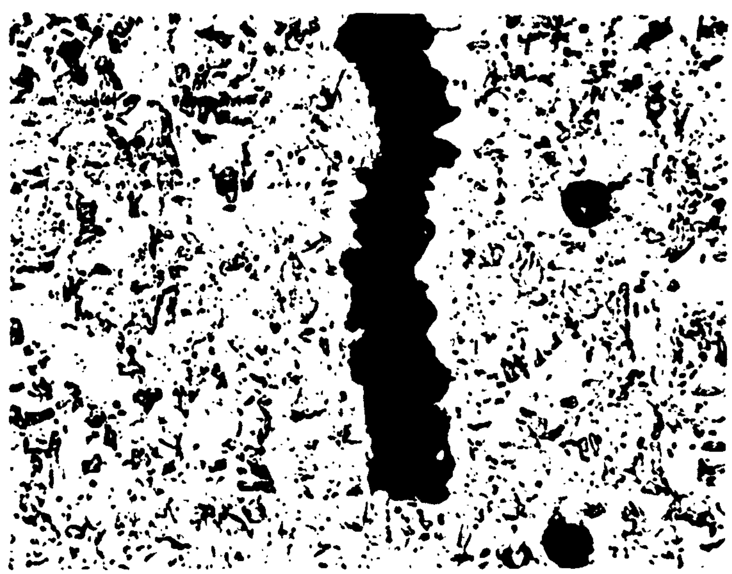
Same Sample as Above (2000X)

Photomicrographs of Stress-Corrosion Cracks in 18%-Nickel Maraging Steel (I-1)

Figure 13



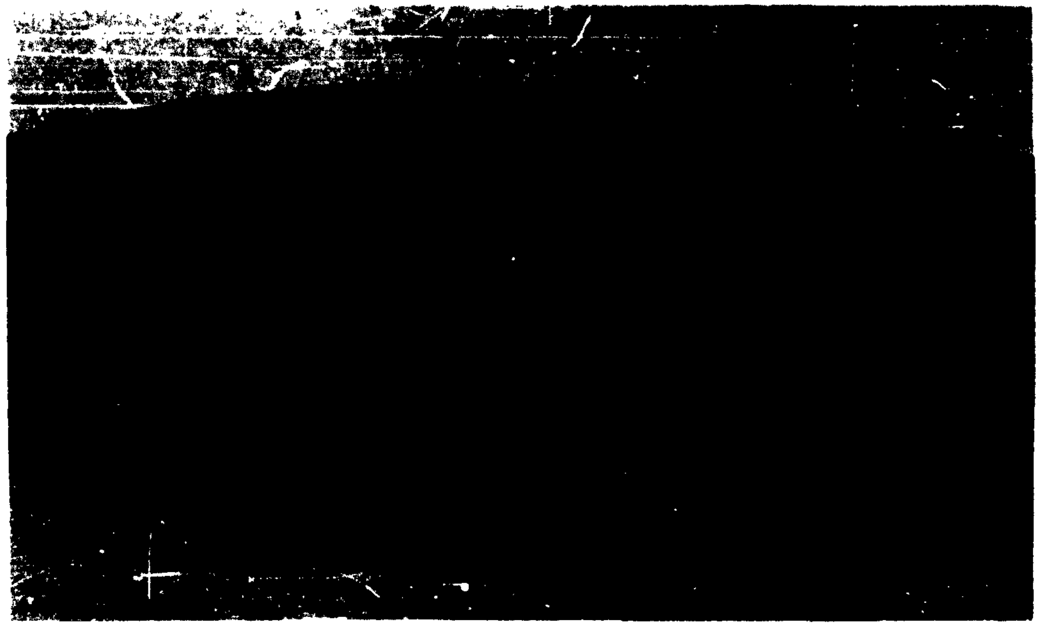
Cross-Section of Annealed and Aged 18%-Nickel Maraging Steel After 90 Days Immersion in Trichlorethylene (10X)



Enlarged View of the Tip of the Shortest of the Above Cracks. Etchant is Diluted Marbles (500X)

Failures in Tricloroethylene

Figure 14



Surface of Cold-Worked-and-Aged 18%-Nickel Maraging Steel After 10-Days at 140°F in High Humidity Stress Corrosion Test. Surface has been Wire-Brushed. (Approx. 2X)

Cross-Section of Above Sample Showing Possible Cracking Along Slip Planes. (10X)

Stress-Corrosion-Crack Pattern in 18%-Nickel Maraging Steel (Group I-3)

Figure 15

View of Surface in Lightly Cracked Area Showing Pitting Attack (100X)

General Structure in Interior of Highly Cracked Area.
Etchant - 10% Ammonium Persulphate-electrolytic. (500X)

Photomicrographs of Stress-Corrosion Cracking in 18%-Nickel Maraging Steel (Group I-3)

Figure 16

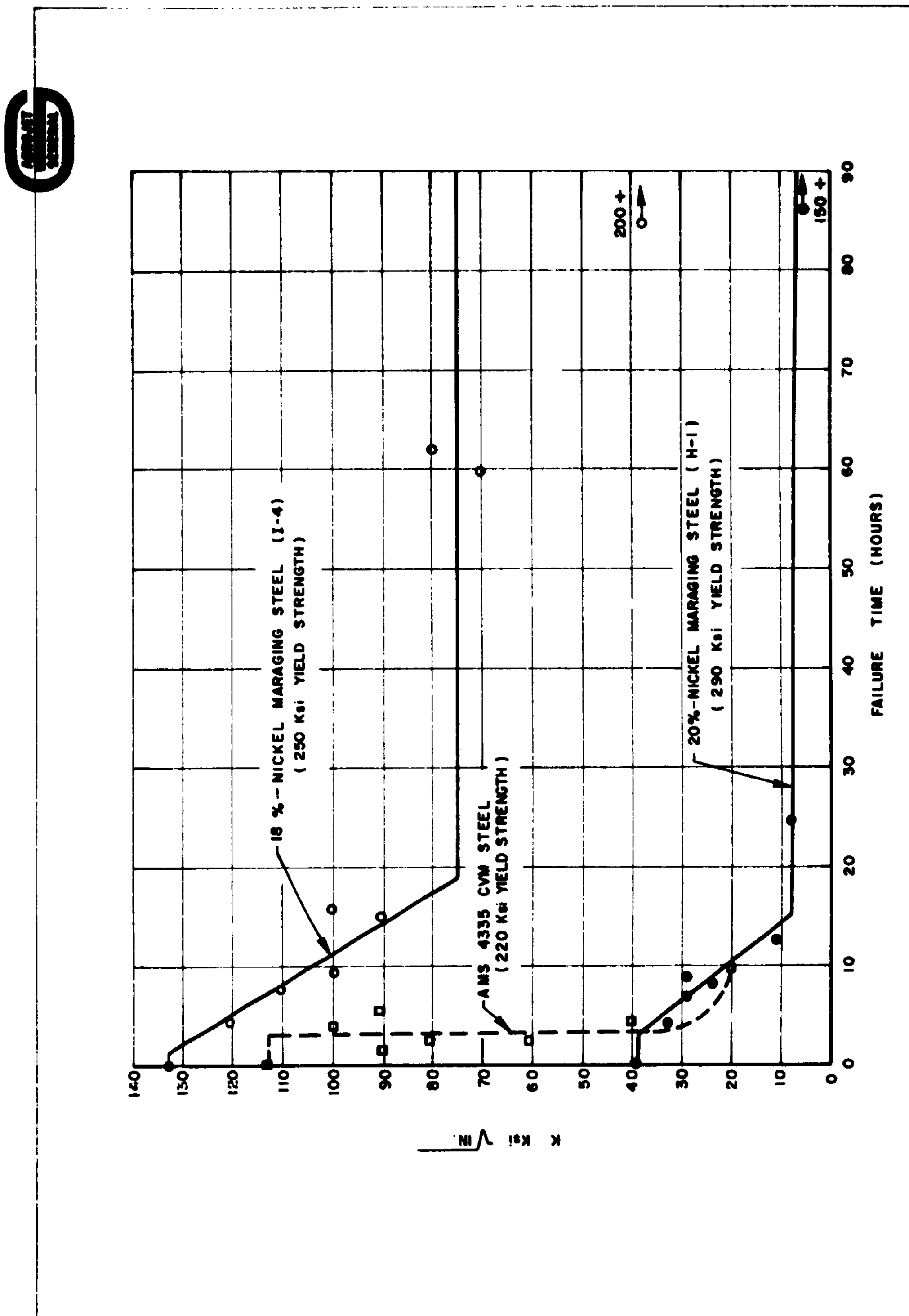
Cross-Section of Welded and Aged 18%-Nickel Maraging Steel After 55 Days Immersion in 4% Soluble Oil Solution.

(10X)

Enlarged View of Fracture Origin in Weld Heat-Affected Zone. Etchant is Diluted Marbles Reagent. (80X)

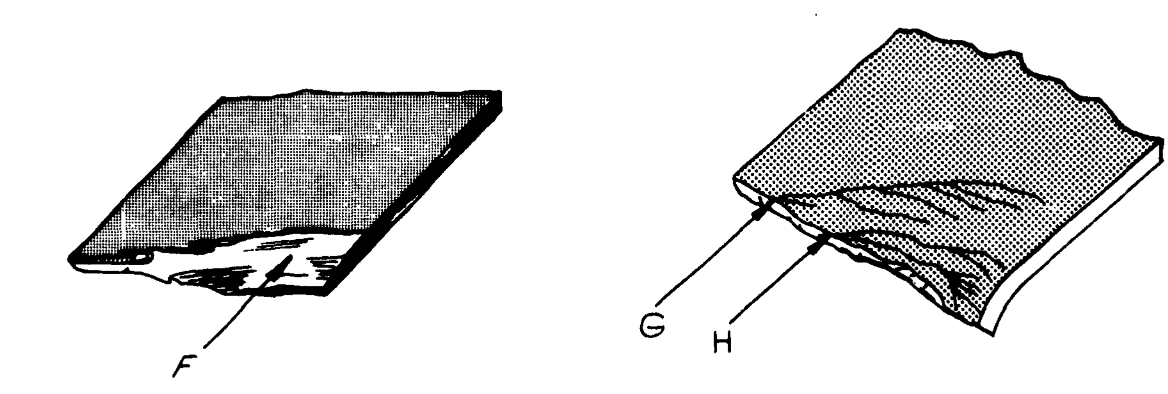
Failures in Welded Samples

Figure 17



EFFECT OF VARYING STRESS ON FAILURE TIME OF CENTER-NOTCHED SAMPLES IN 3% NaCl SOLUTION

Figure 18



Uncoated H-11 Steel, Failed in 2.5 Hours in Aerated 3% Salt Water

20%-Nickel Maraging Steel (Group H-1), Failed in 1 Hour in 0.25%-Sodium-Dichromate Solution

18%-Nickel Maraging Steel (Group I-3), Failed in 626 Hours in Aerated Distilled Water

18%-Nickel Maraging Steel (Group I-1), Failed in 100 Hours in 0.25% Sodium Dichromate Solution

Location of Electron-Microscope Fractographs

Figure 19

Electron-Microscope Fractograph of H-11 Steel (View A, Figure 19) Showing Typical Area of Brittle Fracture, with Multiple Fracturing (17,500X)

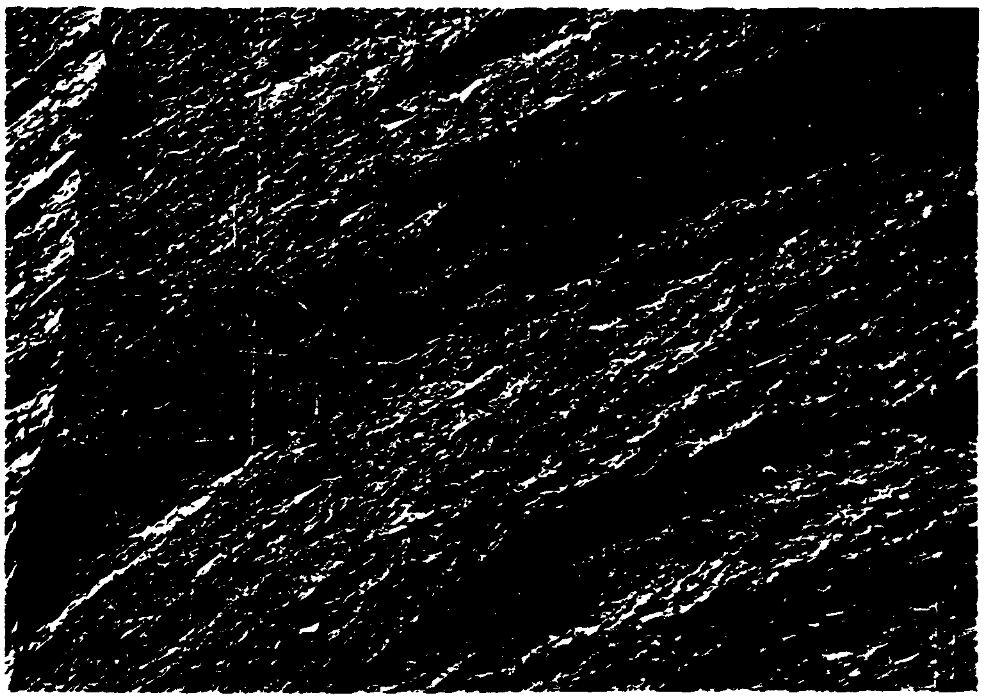
Figure 20

Electron-Microscope Fractograph of H-11 Steel (View B, Figure 19) Showing Typical Fracture-Initiation Area, with Multiple Fracturing in Areas That May Have Microstructure Modeling Possibly Caused by Corrosion (35,000X)

Figure 21

Electron-Microscope Fractograph of 20%-Nickel Maraging Steel (View C, Figure 19) Showing Ductile-Fracture Domains, with Prominent Inclusions Along Domain Grains and Surface of Grains Showing Modeled Effect of Ductile-Adhesion Fracture (17,500X)

Figure 22



Electron-Microscope Fractograph of 20%-Nickel Maraging Steel (View D, Figure 19) Showing Brittle-Type Fracture Occurring Stepwise Along Direction of Failure, With Orientation Change to Procession of Fracture at Left (17,500X)

Figure 23

Electron-Microscope Fractograph of 20%-Nickel Maraging Steel (View E, Figure 19) Showing Intergranular-Type Fracture, with Evidence of Inclusions in Fracture Domains and Indications That Sample Failed in Tension (7000X)

Figure 24

Electron-Microscope Fractograph of 18%-Nickel Maraging Steel (View F, Figure 19) Showing Stepwise Brittle Fracture and Areas of Microcracking Along Vaguely Outlined Domains (17,500X)

Figure 25

Electron-Microscope Fractograph (View G, Figure 19) Showing Pure Brittle Fracture. Modeling Effect in Fracture Grain Probably due to Body-Centered Cubic Precipitate. (20,000X)

Fractograph View

Figure 26

Electron-Microscope Fractograph (View H, Figure 17) Showing Glide Decohesion Striations in an Essentially Brittle Fracture. (20,000X)

Fractograph View